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AN EXAMINATION OF THE FACTORS AFFECTING THE THRUST REQUIREMENTS AND THE HOVER AND SHORT TAKEOFF PERFORMANCE OF SEVERAL JET V/STOL FIGHTER CONCEPTS

by

Richard E. Kuhn

AVIATION AND SURFACE EFFECTS DEPARTMENT

DTNSRDC/ASED-78/08

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A Study of five jet vertical takeoff and landing fighter concepts was made considering height and attitude control, ground effect, ingestion losses, control bleed effects, installation losses, component weights, and short takeoff performance. A fixed gross weight of 35,000 pounds was assumed for each of the following concepts studied:

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- Lift Plus Lift/Cruise,
- Lift/Cruise Plus Remote Burner,
- Lift/Cruise (bleed air for control),
- Vertical Attitude Takeoff and Landing, AND
- Tilt Wing.

Since total mission performance was not included in the study, no conclusion as to the "best" concept is made, but rather some of the mission/concept tradeoffs are presented.

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ABSTRACT

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Lift Plus Lift/Cruise
Lift/Cruise Plus Remote Burner
Lift/Cruise (bleed air for control)
Vertical Attitude Takeoff and Landing
Tilt Wing

Since total mission performance was not included in the study, no conclusion as to the "best" concept is made, but rather some of the mission/concept tradeoffs are presented.

ADMINISTRATIVE INFORMATION

The author, Mr. Richard E. Kuhn, completed this work while on a special one-year assignment from the NASA Langley Research Center to DTNSRDC. The purpose of his assignment was to assist with Navy VSTOL aircraft technology assessment and planning.

INTRODUCTION

The requirements of combat maneuverability have resulted in some fighter aircraft flying today with thrust-to-weight ratios greater than 1 for normal takeoff weight. At first glance this would seem to make vertical takeoff and landing (VTOL) performance rather easy to achieve. However, there are many compromises to make and losses to overcome in configuring a supersonic fighter aircraft to provide adequate control and thrust margin for hovering and vertical takeoff and landing. The manner in which these compromises will be taken and the

concept that is eventually chosen will depend on: (1) the mission requirements (maneuverability, sustained supersonic cruise, subsonic loiter, etc.); (2) the basing provisions provided (How often is vertical takeoff (VTO) required? How often can short takeoff (STO) be used? Can special takeoff and landing platform be provided?); and (3) the efficiency attainable in converting engine thrust to useful lift with adequate control.

The present study was undertaken to identify and quantify the VTOL related induced effects and installation losses that affect the sizing and performance of several jet VTOL fighter concepts. The purpose was to evaluate the relative importance of these factors and to provide a backdrop for commenting on the advantages and disadvantages of the several VTOL concepts as well as to highlight the need for additional work to upgrade the presently available data base and estimating methods. Since total mission performance was not evaluated, the results should not be used as the basis for concept selection.

Five concepts were examined:

1. Lift Plus Lift/Cruise
2. Lift/Cruise Plus Remote Burner
3. Lift/Cruise Plus Bleed Air For Control
4. Vertical Attitude Takeoff and Landing
5. Tilt Wing

STUDY METHOD

To minimize the complexity and time required in a preliminary analysis, a fixed gross weight of 35,000 lb was assumed for each concept. The relative VTO penalties associated with each concept then show up as increases in installed thrust required. The resulting airplanes do not have comparable mission performance; however, the effect on mission radius can be inferred from the impact on useful load available for fuel and armament.

The so-called "supercruiser" mission involving extended cruise at supersonic Mach numbers was chosen as the starting point because of the challenge presented by low drag shapes, the high fineness ratios required for low drag, and the anticipated problems of obtaining these low drag shapes due to engine size and location constraints. The aerodynamic design of Reference 1 was used as the baseline; however, use of this design should not be interpreted as advocating this type of mission over any other. Also, the work that had been done on a previous study of a VTOL supercruiser concept provided an extensive data base in terms of the aerodynamic characteristics, inboard profiles locating engine, fuel and key equipment as well as weight, balance and moments of inertia data.

HEIGHT AND ATTITUDE CONTROL

The control criteria suggested in AGARD Report 577 were used as the basis for determining control power. This document recommends minimum levels of control power for maneuvering and also indicates

typical total levels for VTOL aircraft. The initial airplane acceleration in rad/s^2 recommended for each axis is:

	Minimum for Maneuver Only	Typical Total
	rad/s^2	rad/s^2
Pitch	0.40	0.80
Yaw	0.35	0.80
Roll	0.40	1.50

The controls were sized (deflection or control jet thrust required) to provide the typical total levels recommended for each axis.

The engine thrust increments required for attitude and height control were determined to be the greater of:

1. The thrust required for full control on whichever axis requires the greatest thrust increment;

2. Simultaneous application of all controls to provide the "Minimum Maneuvering" levels; plus trim for a 40-knot wind; plus 0.05-g vertical acceleration;

3. Vertical acceleration of 0.1 g's with all controls neutral.

GROUND EFFECT

In ground proximity the impingement of the jet streams on the ground produces several interrelated effects. The outward flow of the jet sheet from the point of impingement entrains ambient air, lowers the pressure under the wing and body of the aircraft, and produces a down load. For singly or closely placed jets this down load

was estimated using the method of Wyatt.[2] For multiple jets with some distance between them, an upward flow (or fountain) is created at the point where the outward flowing sheets from the jets meet. The lift produced by this upward flow when it impinges on the bottom of the airplane cannot be estimated with confidence. This fountain flow can also lead to hot gas ingestion by the engine inlets if precautions are not taken. Methods of estimating the level of inlet temperature rise are also not reliable.

For any particular configuration experimental programs are required to obtain reasonably reliable estimates of both the aerodynamic suck down and inlet temperature rise. The estimates used in this study illustrate only the approximate thrust penalties involved.

HOT DAY AND HOT GAS INGESTION LOSSES

The thrust loss due to increase in temperature of the air entering the engine, from either hot gas ingestion or elevated ambient temperatures, was assumed to be 0.4 percent of the engine operating thrust per degree C of inlet temperature rise.

CONTROL BLEED EFFECTS

The thrust loss due to high pressure bleed from the compressor depends on the engine cycle. For this study, assuming low bypass ratio engines, the loss was assumed to be 2.8 percent of engine operating thrust for each 1.0 percent of engine mass flow removed. However, if used in downward directed jets, this air contributes to

the total lift and some of this loss is regained. This lift contributio., was estimated to be 0.7 percent of engine operating thrust for each 1.0-percent engine mass flow.

INSTALLATION LOSSES

Inlet and power takeoff (for services other than control bleed) losses were assumed to be 2 percent of the engine operating thrust. For nozzles that deflect the exhaust 90 deg, the nozzle loss was assumed to be 5 percent of the nozzle operating thrust. In addition, an out-of-ground-effect down load is induced by the lifting jets. This down load is a function of the planform area to jet area ratio. This would be about a 1.0-percent loss for the horizontal attitude type studied here.

WEIGHTS

Weights were estimated on the basis of an examination of the weight statements of several current high performance fighters and design studies of proposed VTOL fighter configurations. The following assumptions were used:

Propulsion		
Engines		W/T
Lift/cruise-basic engine		0.10
Lift engine-basic engine		0.05
Nozzles		
90-deg vectoring		0.039
Combined angle		0.026
Lift engine lateral vectoring		0.010
Remote Burner		0.016
Reaction Control System (bleed air)		
Pitch/yaw		0.006
Roll		0.002
Installation - 20 percent of weight (engine and nozzle remote burner)		
Structure		
Wing	7 lb/ft^2	
Tails	4 lb/ft^2	
Body	12-percent ground weight	
Landing Gear	4.5-percent ground weight	
Avionics	1900 lb	
Equipment		
Hydraulic, Electric, etc.	3200 lb	
Crew	200 lb	

CONCEPT DESCRIPTIONS AND VTOL PERFORMANCE

LIFT PLUS LIFT/CRUISE CONCEPT

The configuration developed is shown in Figure 1. This configuration is based on a previous study of a vertical/short takeoff and landing (V/STOL) supercruise concept which provided a convenient starting point because of the work that had been done on the aerodynamic configuration and on developing inboard profiles to locate fuel, key equipment and provide realistic weight, balance and moment of inertia data.

To stay within the aerodynamic lines and maintain the low drag of the baseline configuration, the lift engines are stowed in a horizontal position during cruise and rotated 90 deg to the vertical for takeoff and landing. This places the cruise engine inlet behind the lift engine and immediately in front of the fountain flow that will develop when hovering in ground effect. To minimize hot gas ingestion, the cruise inlet is blocked completely during takeoff and landing, and auxiliary inlets located on top of the aircraft are made large enough to pass all the air required by the engines. Part of the canopy is hinged to move aside (or attached to the lift engine inlet door) to allow the lift engine inlet to open. Half of the avionics equipment, the auxiliary power unit, and much of the electrical equipment and other fixed equipment is located in aft fuselage fairings to achieve center of gravity (c.g.) compatibility with the aerodynamic center. Fuel is carried in the inboard wing panel and in the fuselage ahead of, as well as above and between, the engines.

The lift/cruise engines violate the basic aerodynamic lines only slightly as shown in Figure 2. The complete area distribution and the effect of the increased volume in the aft sections of the airplane were not evaluated; however, the small changes shown should not create a serious problem.

The thrust and control requirements are shown in Figure 3. Pitch control is obtained by varying the thrust of the lift and lift/cruise engines, yaw control by lateral deflection of the lift engine thrust, and roll control by bleed air from the lift engines ducted to nozzles at the wing tips. Multiple ducts will be required to get the bleed air through the thin outer wing panels to the roll control nozzles.

The thrust required for height and attitude control is set by the full pitch control requirement of 0.8 rad/s^2 assumed for this study. In hovering the lift engines support about 35 percent of the airplane weight. For full nose-up control with a forward c.g., support must go up to about 47 percent while the lift/cruise engine thrust is reduced the same amount. Similarly, for nose-down control the thrust of the lift/cruise engines must be increased from 65 percent to about 77 percent of the weight. The thrust increment required for height and attitude control is about 26 percent of the aircraft weight. Yaw control requires 30-deg lateral deflection of the lift engine. Roll control requires about 10-percent bleed from the lift engines and requires that the lift engines be oversized further by about 600 lb each.

There have been many investigations of hot gas ingestion. Data are available on the AV-6A (Reference 3), predecessor to the

Harrier, and the VAK 191 (Reference 4). These data show that the inlet temperature rise is very configuration related (and varies with height, attitude and wind velocity and direction as well as time spent in hovering). Reliable analytical methods for predicting inlet temperature rise are not available. The approach taken in the present study was to design to minimize ingestion. The AV-6A showed average temperature rises of about 10 C. The VAK 191 inlet temperature rise was generally less than 10 C with occasional levels of 30 C and higher. For the present example the inlet temperature rise is assumed to be 10 C, causing about a 4-percent thrust loss.

The aerodynamic forces on the configuration hovering in ground effect can be acting either upward or downward. The sheet of high velocity air, flowing outward from the point at which the jets impinge on the ground, entrains air which reduces the pressure under the aircraft and thus causes a down load. Where the outward flowing sheets from multiple jets meet, a stagnation line is created and the flow is directed upward. The up flow that impinges on the aircraft causes a lifting force. The ground induced moments are determined by the distribution of planform area, the location of the lifting jets, the location of the up flow, and the attitude of the aircraft with respect to the ground.

There is a temptation to try to configure the airplane to maximize the up flow and thus the lifting force. However, if all jets are hot (the front jet on the Harrier contains only the heat of compression from the fan pressure ratio), this will aggravate the hot gas ingestion problem. In the lift plus lift cruise concept the jets

are located near the airplane centerline with only fore and aft distribution in an attempt to minimize the hot gas ingestion.

The aerodynamic ground effects, Figure 4, have been estimated using the method proposed by Wyatt[2] for single jet configurations. The suck down from the front jets was assumed to be based on the planform area forward of the stagnation line (estimated on the basis of the thrust split between the lift and lift/cruise engines), and the suck down from the rear jets was based on the planform area aft of the stagnation line. Due to the predominance of area aft of the stagnation line, this results in a sizeable nose up moment. A fountain flow exists at the stagnation line and impinges on the configuration forward of that line. Although reliable methods for estimating the resulting up force are not available, it would be small for this configuration but would increase the nose up moment and decrease the suck down. On the other hand, other data indicate that Wyatt's method may underestimate the suck-down forces. A range of uncertainty, such as shown in Figure 4, exists and model tests are required for each specific configuration to obtain reliable estimates. The landing gear length was chosen to limit the estimated down load for this configuration to about 8 percent, most of which must be made up by increasing the thrust of the lift/cruise engines.

Additional allowances for hot day and installation losses, inlet, power takeoff, and base loss out of ground effect increase the total thrust-to-weight ratio required to 1.55, or two 17,100-lb thrust lift/cruise engines and two 10,000-lb thrust lift engines.

LIFT/CRUISE PLUS REMOTE BURNER

One proposal to avoid the disadvantages of having two dissimilar engines in the aircraft has been to use a multiple stream engine with provision to take some of the airflow (at pressure ratios of 3 to 4) to a burner and nozzle located where the lift engines would be. Such a configuration is shown in Figure 5. In this concept, all the airflow required for VTOL operation must go through the lift/cruise engines resulting in a large increase in engine size. The resulting increase in cross-section area (Figure 6) and volume in the aft section of the fuselage are large and will adversely affect the supersonic aerodynamic efficiency. On the other hand, there is more thrust available for acceleration and maneuver.

The control and thrust buildup for this concept is shown in Figure 7. The size of the remote burner is set by the requirement for full nose up trim and control. The total thrust required for pitch control is not increased in the lift plus lift/cruise concept because control can be obtained by shifting mass flow (and thrust) forward for nose up control and aft for nose down.

Yaw control requires ± 30-deg lateral deflection of the burner thrust. The increase in thrust required to maintain the vertical component of thrust constant plus the 0.05-g vertical acceleration is less than control neutral requirement of 0.1-g vertical acceleration, which in this case sets the height and attitude control thrust margin requirement.

High pressure bleed air is used for roll control in order to keep the duct size compatible with the thin outer wing panels.

The thrust allowances for hot gas ingestion, ground effect, hot day, and installation losses are similar to those for the lift plus lift/cruise configuration. Because of the smaller allowance required for height and attitude control, the total thrust-to-weight ratio required (about 1.43) is considerably less than the ratio required in the lift plus lift/cruise concept.

The engine/burner system must be sized, for this example, to provide up to a 42/58 burner/main nozzle thrust split for VTOL operation. A further increase in burner size is desired for short takeoff operation.

LIFT/CRUISE WITH BLEED AIR CONTROL

The lift/cruise configuration shown in Figure 8 evolved from the conflicting desires to locate the vectoring nozzles as close to the c.g. as possible to minimize bleed air requirements for trim while minimizing the surface area aft the nozzle to minimize the lift loss in transition and STO operation. The latter requirement meant departing from the baseline configuration in favor of an aft tail. Even so, it was not possible to move the c.g. and aerodynamic center far enough aft to get the nozzle very close to the wing trailing edge where it should be for the best STO performance. The large size of the engines and their forward position result in major adverse changes in the area distribution (Figure 9). The configuration shown would probably be more appropriate to a mission requiring supersonic dash and maneuverability than to a mission requiring supersonic cruise performance.

The control concept assumed employs continuous bleed to downward directed nozzles at the nose and tail and at wing tips so that the control thrust contributes to lift. Pitch and roll are obtained by shifting thrust forward, aft, or side to side (Figure 10). Yaw control is obtained by lateral deflection of the front and rear pitch control jets. The thrust from the control jets is increased with lateral deflection to keep the vertical component from decreasing (top right of Figure 10). This thrust increase amounts to about 2500 lb for full yaw control -- less than the 3500 lb needed to meet the assumed requirement of 0.1-g vertical acceleration which sets the height and attitude control margins for this configuration.

Because of the forward engine location, auxiliary inlets on top of the airplane are not practical. The hot gas injection margin has therefore been assumed to be about twice that of the earlier configurations.

Allowances for ground effect, hot day, and installation losses are similar as for the earlier configurations. A total of 50,000-lb thrust (T/W = 1.43) is required; 8,400 lb of this is bleed air thrust. Thus, two engines are required, each capable of producing about 21,000 lb of thrust plus about 45 lb/s air for control. These engines would have to be specifically designed since the bleed is much beyond that normally available from conventional engines. The engine frame size would correspond to engines of over 30,000 lb each.

VERTICAL ATTITUDE TAKEOFF AND LANDING CONCEPT

The vertical attitude takeoff and landing (VATOL) concept is assumed to operate from special vertically oriented platforms which it engages with a hook or other device on its nose wheel. The platform is hinged so that the airplane can be lowered to the horizontal and taxi on its conventional gear which is retained. A means is provided to rotate the pilot's seat (or entire cockpit) so that he has normal visual cues during takeoff and landing, and a reaction control system is provided for hover and low-speed flight. In the example used in this study (Figure 11), the engines are fitted with combined angle deflection nozzles. The engines are only slightly larger than the lift/cruise engines in the lift plus lift/cruise configuration and increase the volume at the aft end of the airplane only a small amount (Figure 12).

Thrust vector control characteristics for the VATOL are shown in Figure 13. Pitch control is obtained by deflection of the engine nozzles; ± 12-deg deflection will provide the moment needed to meet the 0.8-rad/s^2 requirement assumed for this study. Yaw control by differential deflection requires only ± 9-deg; combined control at the "minimum for maneuver" level can be obtained with about ± 10-deg deflection. The thrust increase required to maintain a vertical component of thrust equal to the weight is only about 500 lb.

Roll control to meet the 1.5 rad/s^2 assumed for this study is shown to require 25-deg lateral vectoring of the thrust. This would require an increase of 3500 lb in engine thrust to maintain thrust equal to weight. This large lateral deflection, which results from

the transfer of axes as the airplane rotates to the vertical, is probably larger than will actually be required for this concept. The yaw axis with the highest moment of inertia becomes the roll axis which requires the highest angular acceleration, thereby resulting in the large moments and deflections. The handling qualities and control power requirements were established through experience with horizontal attitude V/STOL aircraft which had relatively low moments of inertia about the roll axis and larger trim and upset moments than are likely with the VATOL as conceived here. Additional study including piloted simulations are required to determine appropriate handling qualities and control power requirements for VATOL configurations.

The thrust margin for height and attitude control will remain at about 0.1 thrust-to-weight ratio even if the roll control level is decreased because, under the assumptions of this study, a vertical acceleration with control neutral must be 0.1 g.

Because of the attitude and the expected operation from platforms on the side of the ship, no aerodynamic ground effects, hot gas ingestion, or base loss out of ground effect are expected. Only hot day and installation losses must be added. A thrust-to-weight ratio of 1.20, or two 21,000-lb thrust engines, is indicated.

TILT WING CONCEPT

The tilt wing concept (Figures 14a and 14b) was conceived in an attempt to retain some of the advantages of the VATOL concept while avoiding the need for the special shipboard modifications. In this concept, the wing engines and inlets are tilted about a hinge line as

near to the wing trailing edge as possible. The center of gravity moves up as indicated in Figure 14b. Combined angle deflection nozzles are used for control as in the VATOL concept. Because of the need for a fuselage structure between the engines to support the hinge and tilting mechanism, the cross section through the engine location (approximately at the hinge line, Figure 15) is significantly increased relative to the basic aerodynamic lines; therefore, a significant reduction in supersonic aerodynamic efficiency would be expected.

Because the distance from the airplane c.g. to the nozzle is only about half the distance for the VATOL concept, the nozzle deflections for pitch and yaw control are doubled. The roll control did not increase because with the fuselage remaining horizontal the moment of inertia in roll is only about half that assumed for the VATOL concept. Large combined angle deflections are required for the tilt wing concept.

The thrust allowance for height and attitude control for this concept is determined by the sum of the combined deflections for maneuver control simultaneously on all axes plus a 40-knot cross wind and a 0.05-g vertical acceleration -- adding up to 5500 lb (Figure 16).

Although the inlets are about 30 ft above the deck, a small allowance has been made for hot gas ingestion. Also, a nozzle loss of 2 percent for combined angle deflection has been included. Total thrust-to-weight ratio required is about 1.3, or two 22,700-lb thrust engines.

WEIGHT BREAKDOWN COMPARISON FOR VTOL PERFORMANCE

An approximate breakdown of the weight for each concept is given in Figure 17. For the VATOL the weight penalty of the nose gear hook (for engaging the landing platform) and the mechanism for tilting the pilot in the cockpit to maintain normal visual cues were assumed to be compensated for by the appreciably shorter landing gear on the configuration. A structural weight penalty of about 1500 lb was added to the tilt wing for the tilting mechanism and added wing and fuselage structure.

In general, the useful load fraction decreases as the installed thrust (and, therefore, propulsion weight) increases, clearly showing the need to minimize installation losses and reduce the weight of propulsion system components.

The sensitivity of the useful load to two of the loss parameters, ground effect, and hot gas ingestion is shown in Figure 18. These sensitivities were estimated for the lift/cruise plus remote burner concept. Although the levels differ, the trends are generally applicable to other concepts. If the losses are known early enough in the development process, the thrust level needed can be changed and the effect on useful load will be minimized. If the losses are not known until the aircraft flies, the effects can be considerable. For instance, if the average inlet temperature rise is 20 deg instead of the 10 deg assumed, the useful load will be reduced by about 1400 lb. A similar loss of 1400 lb in useful load would occur if the aerodynamic suck down in ground effect were 12 percent instead of the 8 percent assumed. Although the left-hand portion of Figure 18 is drawn for

ground effect, the slopes apply for any source of thrust loss. An additional 2 percent of thrust loss, due to poorer than expected inlet recovery or nozzle performance, would cause a loss of about 700 lb of available useful load.

STO PERFORMANCE OF CONCEPTS

Most VTOL aircraft can lift considerably more payload if a short deck run is available. The added lift accrues from wing lift and from elimination of hot gas ingestion (above about 50 knots) and ground effect (once past the end of the deck). Also, the lift can be affected, either favorably or unfavorably depending on the configuration, by the jet/free-stream interaction.

Estimates of the overload STO performance of each concept were made. The calculations assumed zero wind over deck and no sink off the bow, that is, the takeoff weights shown are for lift equal to or greater than the weight at the end of the deck run. The thrust was assumed to be 35,000 lb plus the thrust increments required in VTOL for hot gas ingestion and ground effect allowances.

LIFT PLUS LIFT/CRUISE CONCEPT

The power-off aerodynamic characteristics assumed for the lift plus lift/cruise concept (Figure 19) are based on Reference 1 and unpublished data. The useable lift coefficient was taken as 0.75 to avoid the worst of the pitch instability at high lifts which arises from the stalling of the wing outer panels on this configuration.

Although this lift coefficient appears low, it is based on a large reference area (580 ft^2).

The jet induced effects in transition are shown in Figure 20. The interaction of the jet flux with the free stream induces suction pressures beside and behind the jet and positive pressure ahead. For the front jets these pressures result in a down load. Several approaches to estimating these losses using available data (References 5 to 9) produced the uncertainty shown by the shaded band. The line represents the "best guess" and was used in the performance estimates.

There is little area aft of the rear jets (by design). These rear jets should induce a favorable lift, again with a range of uncertainty in the estimate.

The lift available as a function of speed is shown in Figures 21a and 21b. Unfortunately, with the lift engines sized for trim and control in VTOL, the favorable lift induced by the rear jets cannot be used because the diving moment produced by the rear jet thrust must be trimmed out by the front jet, and their contribution is decreasing (Figure 21a). There is a nose-up moment induced along with the lift, but this corresponds to the induced lift loss acting about 1 to 2 jet diameters behind the jet center, which is small relative to the distance from the front jet to the c.g. About 40 percent of the wing lift is used in overcoming these losses. Nevertheless, the takeoff weight can be increased significantly -- to about 40,000 lb, if a 400-ft deck run is available.

If the lift engine size is increased, additional thrust and lift would be available. The VTOL thrust increments due to hot gas

ingestion and ground effect can now be utilized for STOL. (Most of this lift increment is available from the lift/cruise engine and could not be used in STO because the lift engines were not large enough to provide trim.) The favorable jet induced contribution of the rear jets can also be utilized. If lift engine size is increased by about 25 percent (2500 lb per engine; about 1000-lb propulsion system weight), the STO lift can be increased about 10,000 lb for a 400-ft deck run (Figure 21b).

LIFT/CRUISE PLUS REMOTE BURNER CONCEPT

Although with this concept the thrust can be transferred fore and aft, the adverse effects of jet interference if the front burner/nozzle is sized for VTO (Figure 22a) still exist. As with the lift plus lift/cruise configuration, about 40 percent of the wing lift is expended in overcoming these losses. The STO takeoff weight for a 400-ft deck run is about 45,000 lb -- 5000 lb greater than the lift plus lift/cruise configuration because the full thrust increment for hot gas ingestion and ground effect is available and because slightly higher acceleration is available during the ground run.

By oversizing the remote burner about 15 percent (to a 48/52 thrust split) so that the full favorable induced effects of the rear jets can be utilized, an additional 5000 lb takeoff weight can be lifted off from a 400-ft deck run (Figure 22b).

The sensitivity of the STO performance to these jet induced effects and to the operating lift coefficient is shown in Figure 23. The speed at the end of a 400-ft deck run is about 80 knots; the

effective velocity ratio is about 0.09. For these conditions Figure 20 indicates a favorable lift increment of 5 percent of thrust. If it were zero the takeoff weight of the airplane would be reduced by 1800 lb. If the configuration could be developed to increase the induced effect by 3 percent (to 8 percent), the takeoff weight could be increased by 1100 lb, most of which would be useful load. Similarly, the takeoff weight would increase by 1000 lb for each percent increase in lift coefficient.

LIFT/CRUISE WITH BLEED AIR CONTROL CONCEPT

As indicated in the description of the concepts, this configuration evolved from the conflicting desires to locate the jet thrust close to the c.g. to minimize bleed air requirements while minimizing the surface area aft of the nozzle to minimize lift loss in STO operation. The resulting configuration has a smaller wing area (430 ft^2), but the planform should be able to operate at considerably higher lift coefficients for short takeoff. An operating lift coefficient of 1.3 was assumed, giving a wing lift about 30 percent greater than that for the lift/cruise plus remote burner and lift plus lift/cruise configurations. As with the two earlier configurations, the jet induced effects nullify about 40 percent of the wing lift; however, the net takeoff weight for a 400-ft deck run is still about 48,000 lb with the basic nozzle, due largely to the higher wing lift available.

Figure 24 shows the large gains possible if the configuration could be trimmed with the nozzles moved further aft. This arrangement could not be trimmed with bleed air but suggests that the use of the

lift/cruise plus remote burner propulsion system in this type of aerodynamic configuration may be superior to the tailless configuration.

VATOL AND TILT WING CONCEPTS

The wing on both the VATOL and tilt wing concepts must go through stall in transition from hovering to conventional flight and back. The X-13 experience and References 10 and 11 showed that this can be accomplished, but care must be taken to delay the stall to as low a speed as possible. Also, the configuration should have gentle progressive rather than abrupt stall characteristics. A delta wing planform appears desirable. For this study the delta wing configuration of Reference 10 was chosen. The aerodynamic characteristics used are shown in Figure 25.

The thrust required, wing angle of attack, and nozzle deflection required in steady level flight transition are shown in Figure 26. At angle of attack above about 25 deg (below 110 knots) the airplanes will be flying with the wing stalled. The contributions of aerodynamic surfaces to control were not investigated but would tend to decrease above the stall. The nozzle deflections required for trim (Figure 26) suggest that the nozzle down travel (forward when the wing is vertical for hovering) may need to be increased to ensure adequate control through transition.

The STO performance of the tilt wing configuration is shown in Figure 27. High wing incidences (angle of attack) are required for flight at low speeds. Because of the mass and inertia of the wing,

engine, and inlet assembly, the thrust vector cannot be rapidly rotated to the angle required for flight, as can be done with nozzle deflection for the previously discussed concepts. To generate as much acceleration as practical, the wing incidence was assumed to be set at an angle 10 deg below the wing angle of attack required for flight, and the nozzle was deflected aft 15 deg (base stick). Both were held constant during the deck run. At the point of liftoff the airplane would have a nose-up moment from the nozzle deflection and would rotate nose up until the pilot stopped the rotation by forward stick, deflecting the nozzles to the angle required for flight. The tilt wing concept is at a disadvantage at low speeds where high incidences (and therefore, low acceleration forces) are available, resulting in poor acceleration and relatively poor STO performance.

The STO performance of the VATOL configuration is shown in Figure 28. Although all the thrust is available for acceleration, the aircraft cannot rotate to the high angle required for flight during the deck run. For a 400-ft run on a flat deck, the STO weight would be 7000 lb lower than the VTO weight, assuming liftoff at a lift coefficient of 1.3 (assuming no sink off the bow).

If a ski jump is used, appreciably larger takeoff weights can be achieved.* The airplane leaves the ski jump at a speed and lift below that required for equilibrium flight; but the ski jump has imparted upward momentum, and the aircraft continue to gain speed while using up the upward momentum and rotating to the flying attitude. With the

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*Reported informally by R. Case ("A Preliminary Assessment of the Ski-jump Takeoff Technique," DTNSRDC TM-16-77-138, Sep 1977).

VTOL control system, about 1 second is required to rotate to the flying attitude, and equilibrium flight is reached before the upward momentum is consumed. The airplane does not descend below deck level. With a ski jump, a takeoff weight of about 47,000 lb can be lifted from a 400-ft deck. It should be noted that all the other concepts were assumed to operate from a flat deck. A ski jump would further increase the STO performance of all of the concepts.

WEIGHT BREAKDOWN COMPARISON FOR STO PERFORMANCE

The increased takeoff weight possible with a deck run translates into very large increases in useful load. Figure 29, presents a weight breakdown for each concept for a 400-ft deck run. For this comparison the structural weight of the STOVL (short takeoff and vertical landing) configurations has been increased in direct proportion to the gross weight increase (which is felt to be a very conservative assumption).

CONCLUSIONS

As indicated in the Introduction, the "best" V/STOL concept will depend on the mission and the operational and basing concept as well as the effectiveness with which the compromises are handled in assembling the designs. This study has considered only the VTOL and STO related aspects. Total mission performance has not been analyzed; therefore, conclusions as to "best" concept are inappropriate. Nevertheless, some comments can be made with regard to some of the mission/concept tradeoffs.

- If the mission calls for extended supersonic cruise, the lift plus lift/cruise and VATOL concepts appear attractive because of the small engines and better volume distributions possible. On the other hand, the greater thrust required in the lift/cruise and lift/cruise plus remote burner concepts should be of value in missions requiring high maneuverability.

- If the special platforms for takeoff and landing can be provided, the VATOL concept appears attractive because of the smaller thrust and minimum modifications to conventional airplane layouts.

- If a short deck run can be made available, large gains in takeoff weight and useful load (up to 100 percent greater useful load for a 400-ft deck run) are possible. All concepts profit from a short deck run, but the VATOL requires a ski jump to avoid sinkoff at the end of the deck. The other concepts would achieve even greater payload advantages if a ski jump were available.

- For the divided thrust concepts, the front element (lift engine or remote burner) will be sized by the short takeoff requirements.

- All concepts require significant propulsion system development. The lift/cruise concept using bleed air for control will require very large amounts of high pressure air (up to two or three times the bleed rate of the Harrier because of the greater moments of inertia and all jets being hot in a supersonic configuration). This requirement dictates development of a special engine to provide high airflow for control. An attractive alternate is to use some of the emerging variable cycle technology to make it possible to duct some of

the fan air to a remote burner located forward in the aircraft to provide trim and control. Current work along this line should be continued, as should work on a 90-deg vectoring nozzle (required for horizontal altitude types), and combined vectoring nozzles required for VATOL and tilt wing concepts.

- The thrust allowance for height and attitude control can be large. The assumptions of this study are based on data from AGARD Report 577 in which the aircraft was assumed to bank or pitch in order to accelerate in the desired direction. Some current work suggests that stabilizing the aircraft in attitude and translating the aircraft by direct vectoring of the nozzles may be less demanding. This work includes the effects of operating from a moving deck and, along with other investigations of the effects of moving deck, should be continued. An early resolution of the handling qualities and control system requirements for operating from moving decks is needed.

- The VATOL concept has unique handling quality characteristics because of the unique pilot attitude and the different moment of inertia distribution (roll is the axis of maximum inertia rather than least as in other concepts). Simulation to study the effects of pilot attitude and orientation as well as to determine the control power requirements is needed.

- The hot gas ingestion and aerodynamic suck down in ground effect can be large for horizontal attitude concepts and are highly configuration dependent. Design arrangements that minimize suck down tend to aggravate the hot gas ingestion problem. Work should continue on configuration and operating techniques to minimize these losses.

One effective approach, if it can be provided at the takeoff and landing site, is to use an elevated, perforated platform or grating. This approach effectively eliminates both hot gas ingestion and suck down but requires special shipboard modifications.

- The jet induced effects in transition and during short takeoff operation can be either favorable or unfavorable, depending on the location of the jet with respect to the wing. The lift/cruise plus remote burner concept offers the possibility of locating the main jets near the wing trailing edge to produce favorable effects and improved STO performance. Continuing investigation of configuration and nozzle location effects are needed.

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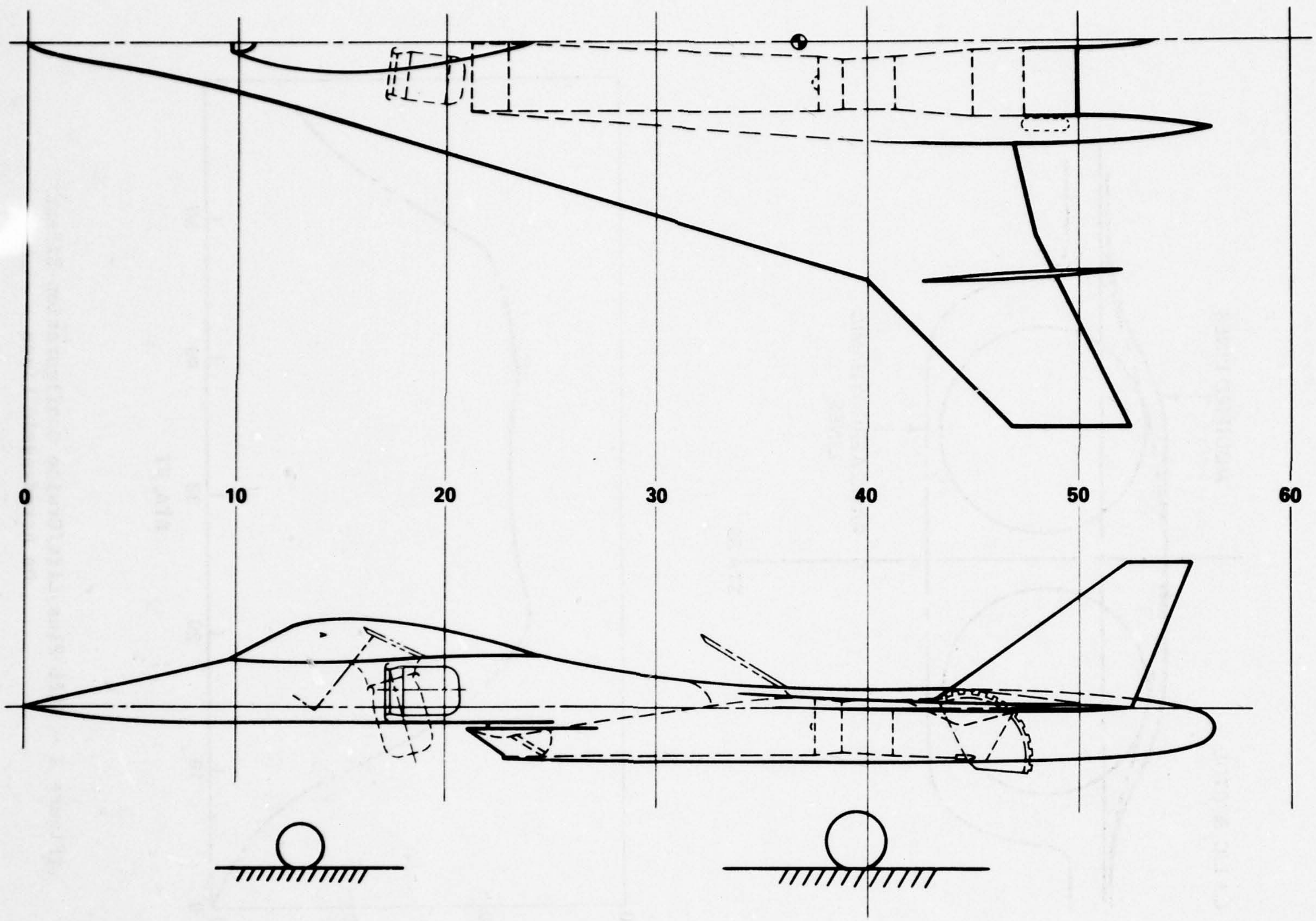
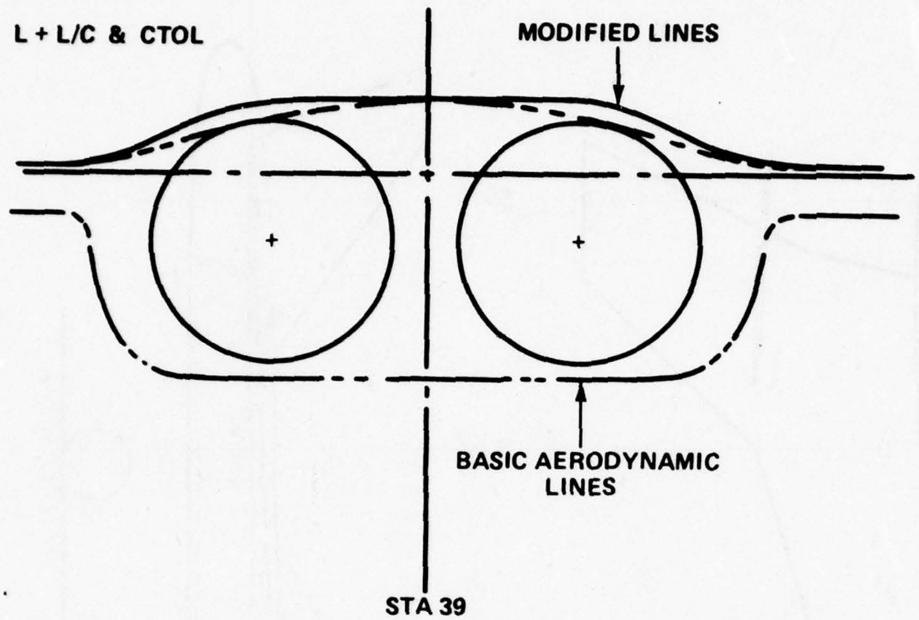


Figure 1 - Lift Plus Lift/Cruise Configuration



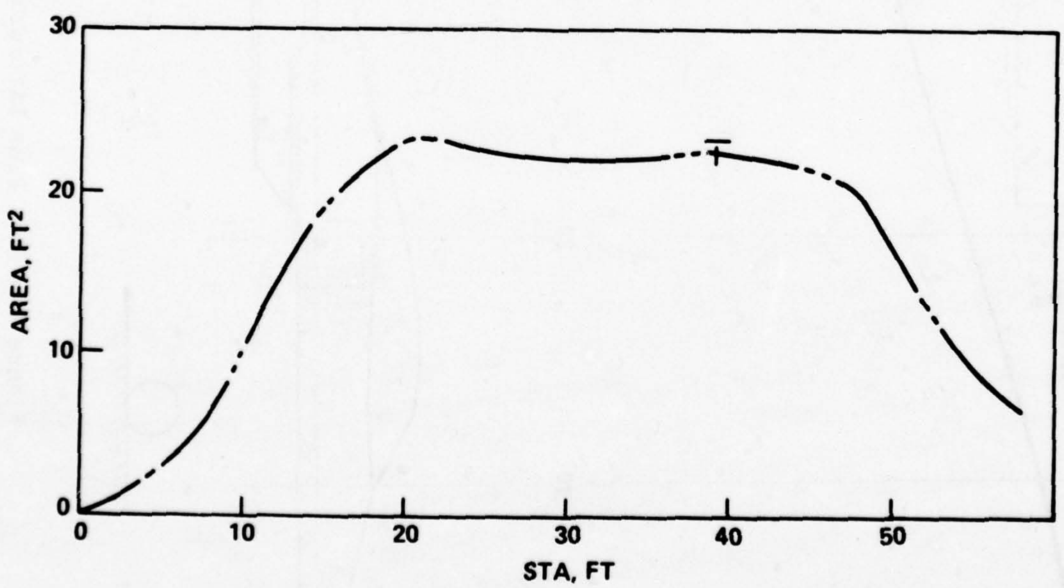


Figure 2 - Lift Plus Lift/Cruise Configuration Effect on Aerodynamic Lines

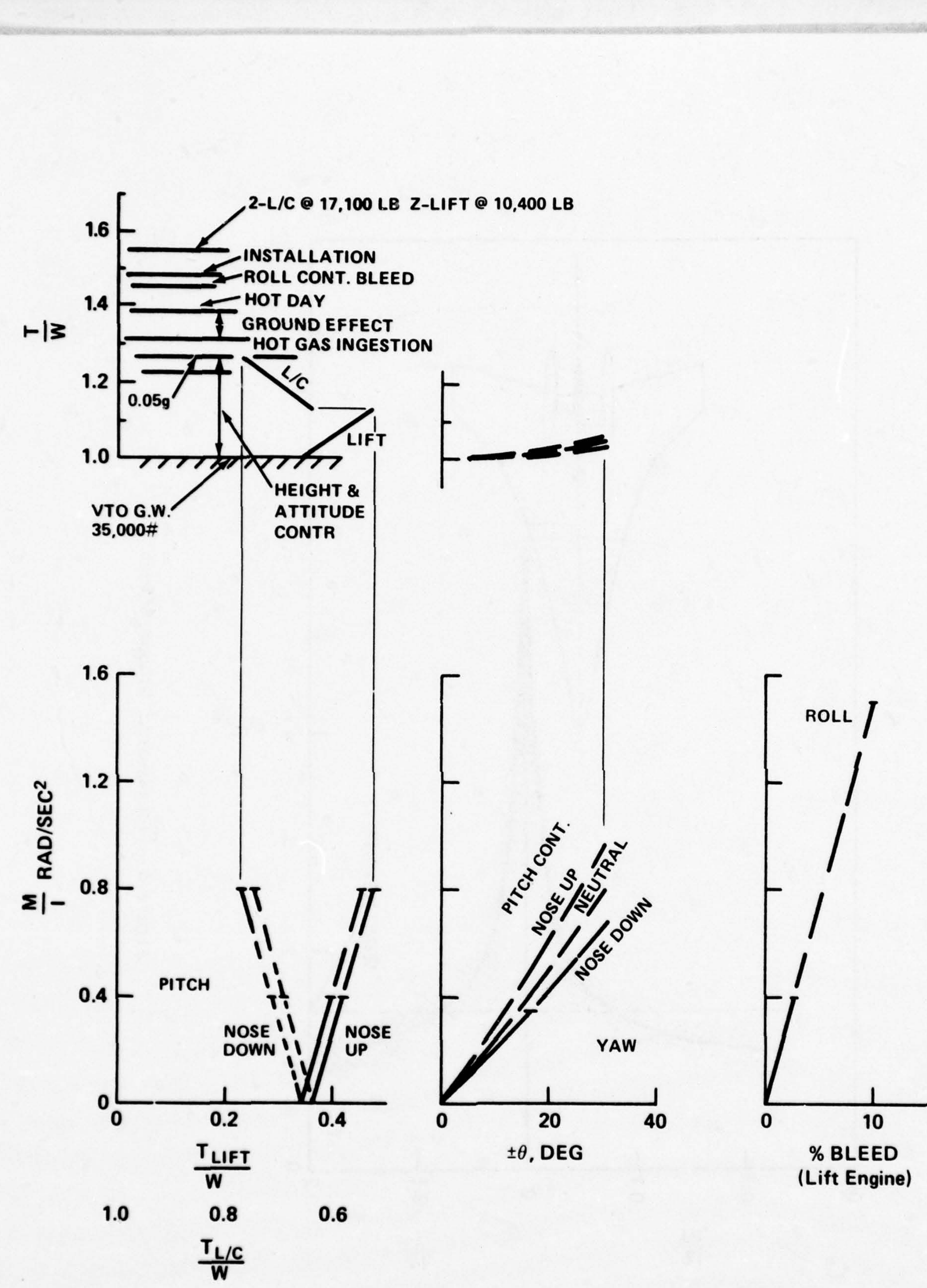


Figure 3 - Lift Plus Lift/Cruise Control and Thrust Buildup

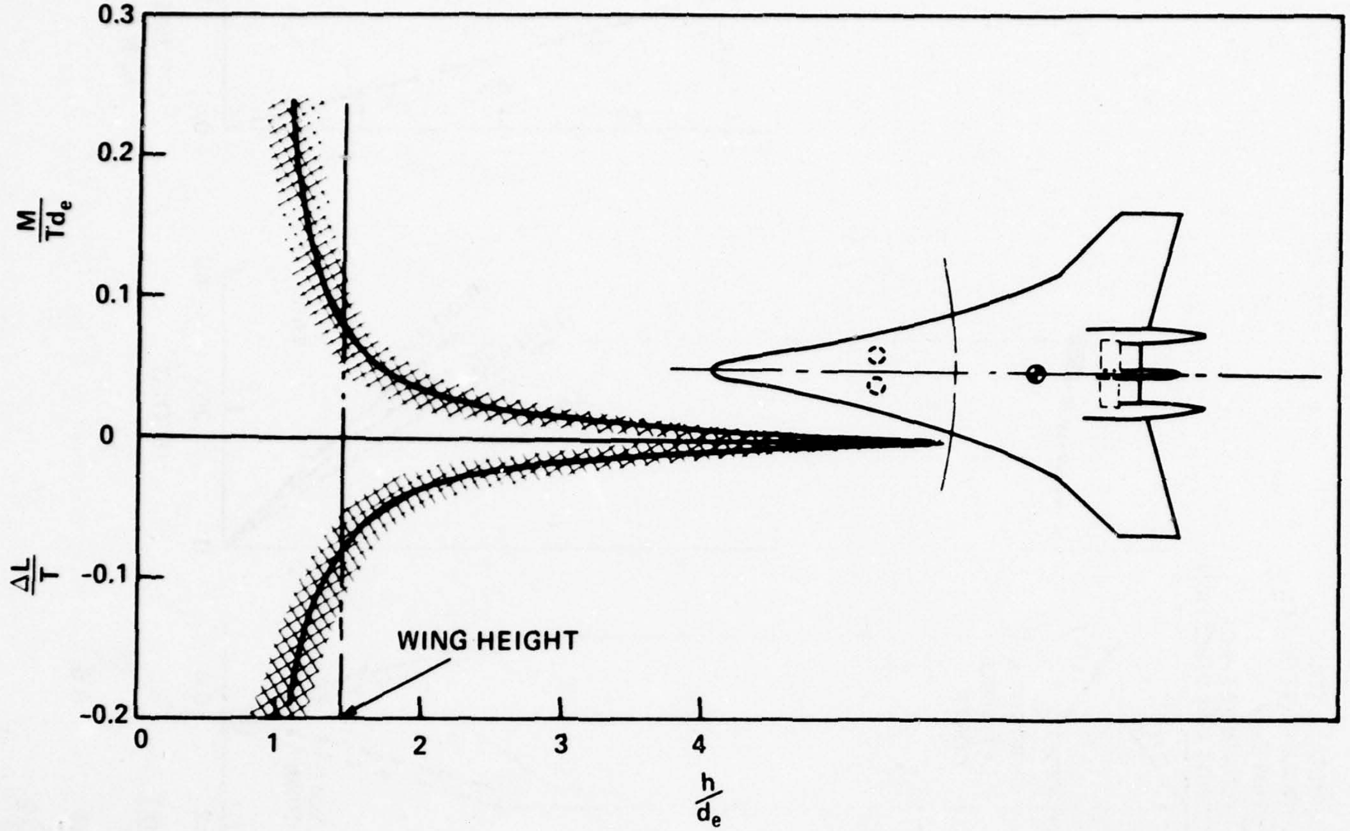


Figure 4 - Aerodynamic Ground Effect

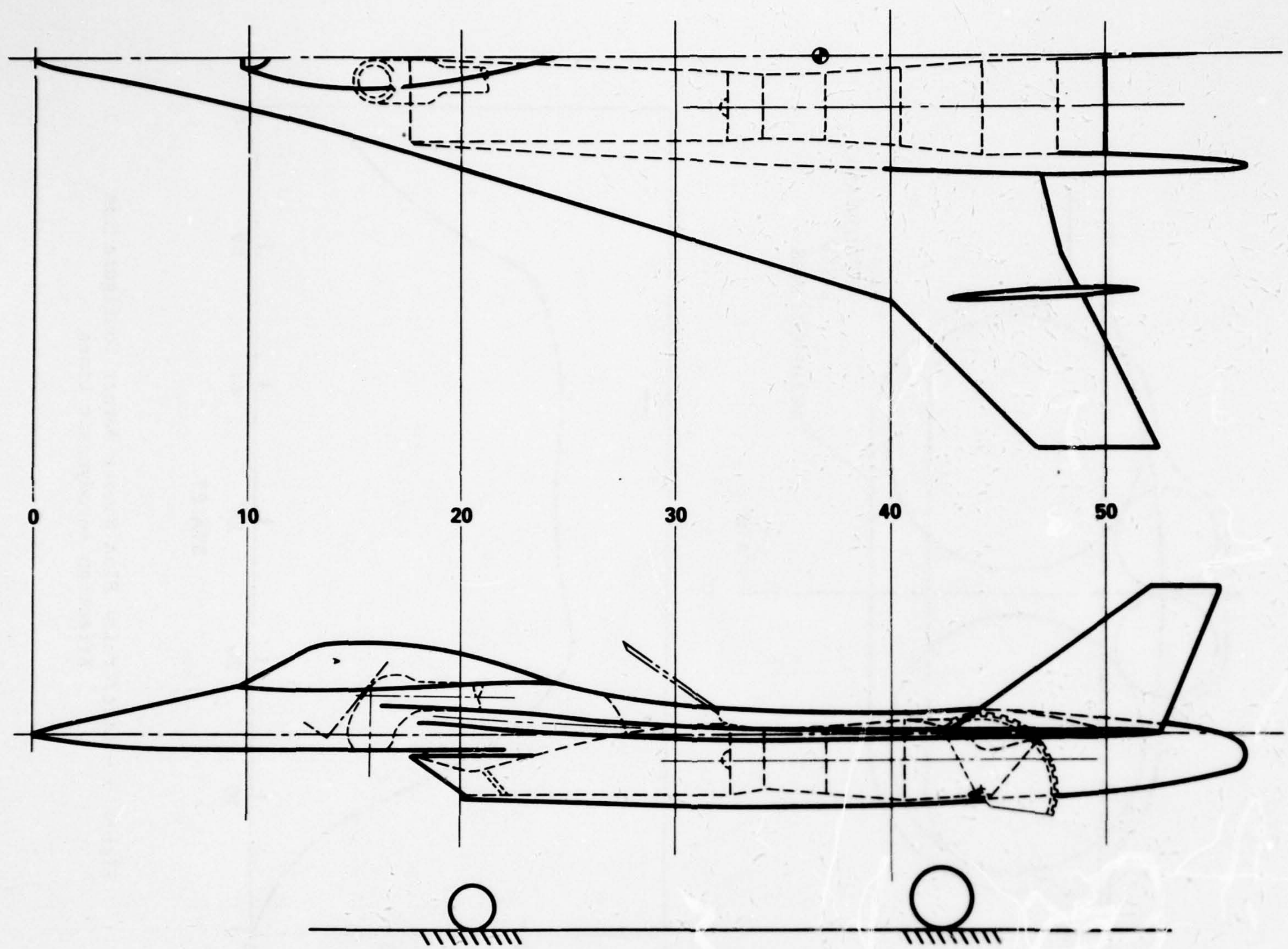


Figure 5 - Lift/Cruise Plus Remote Burner Configuration

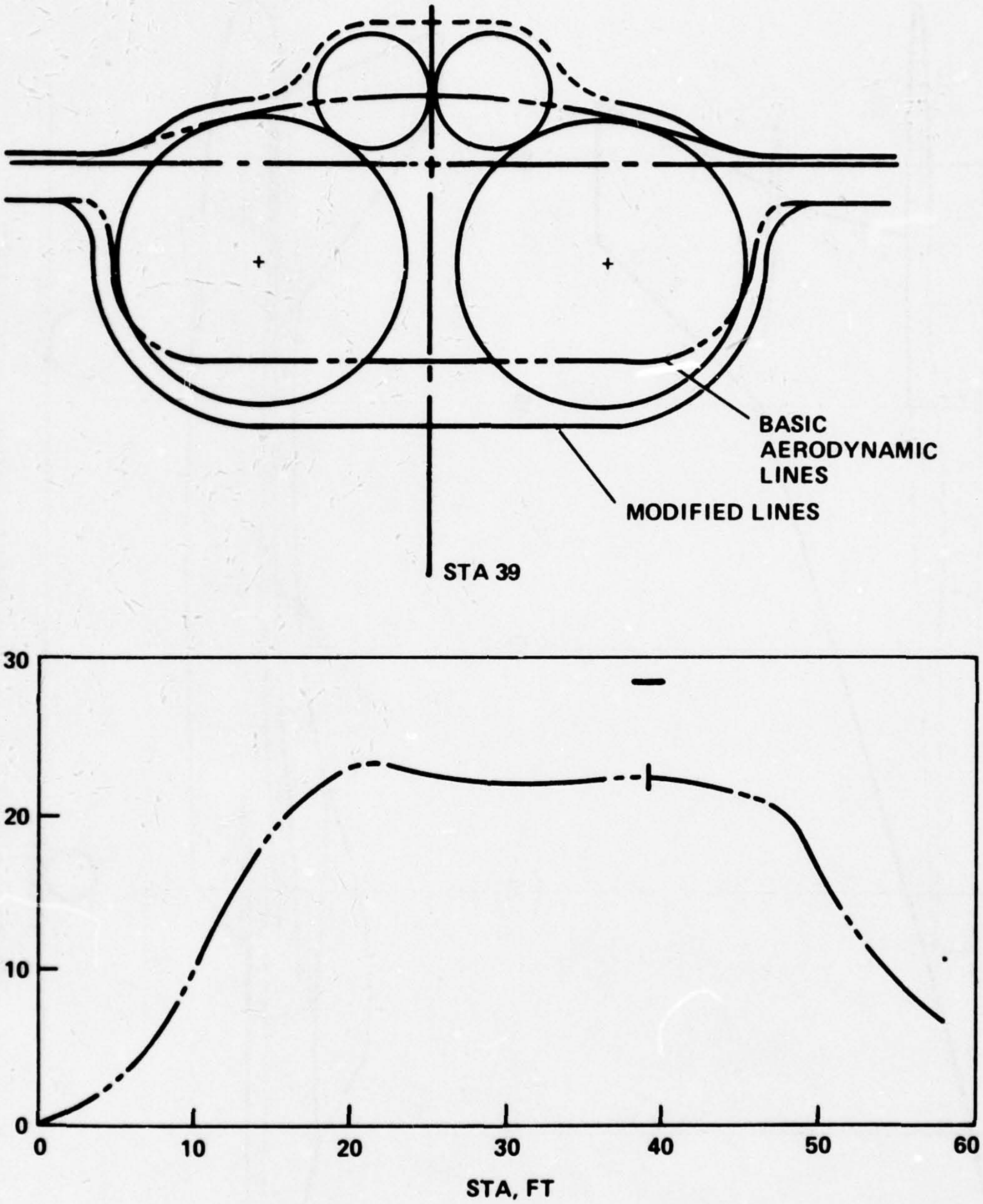


Figure 6 - Lift/Cruise Plus Remote Burner Configuration Effect on Aerodynamic Lines

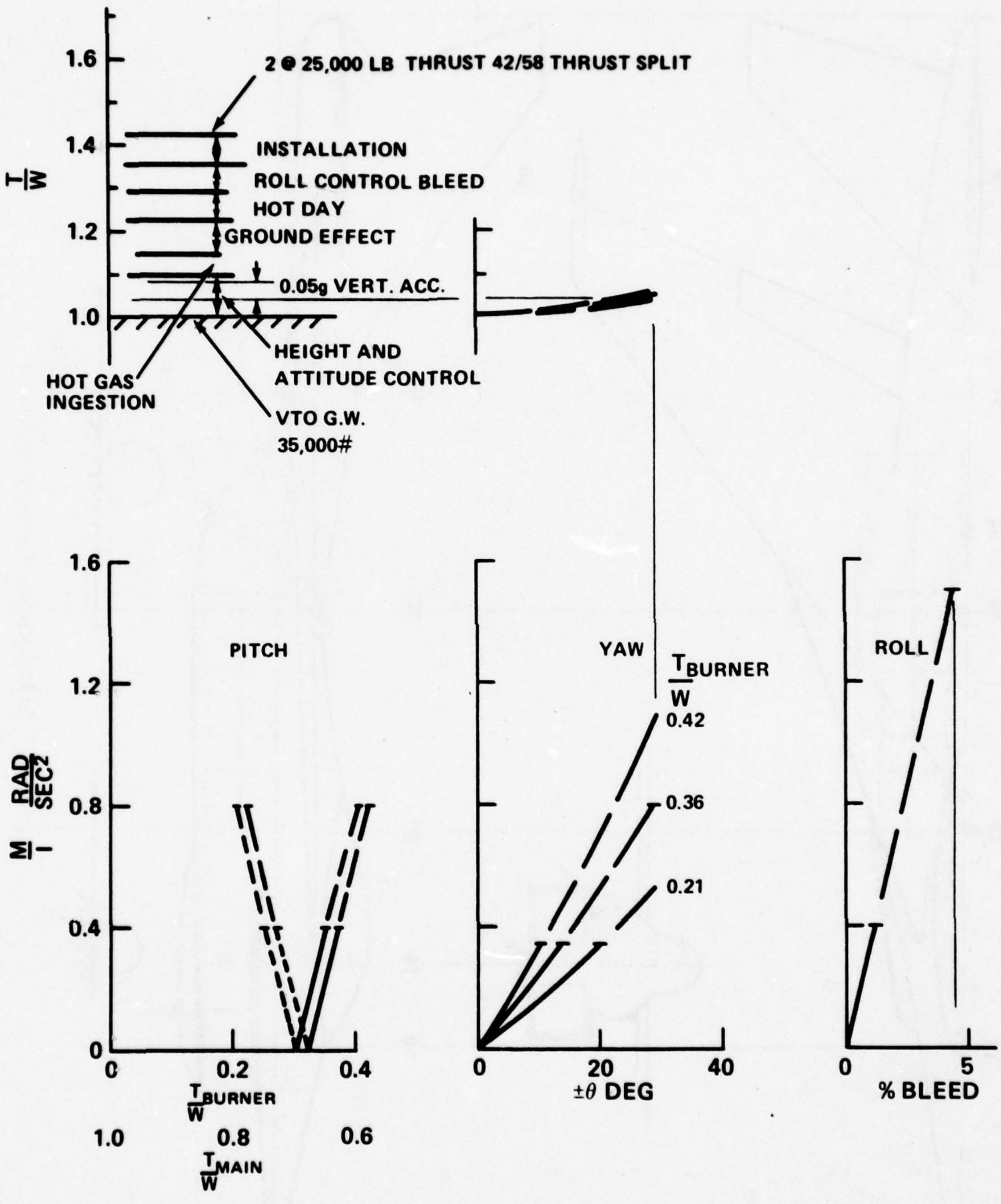


Figure 7 - Lift/Cruise Plus Remote Burner Control and Thrust Buildup

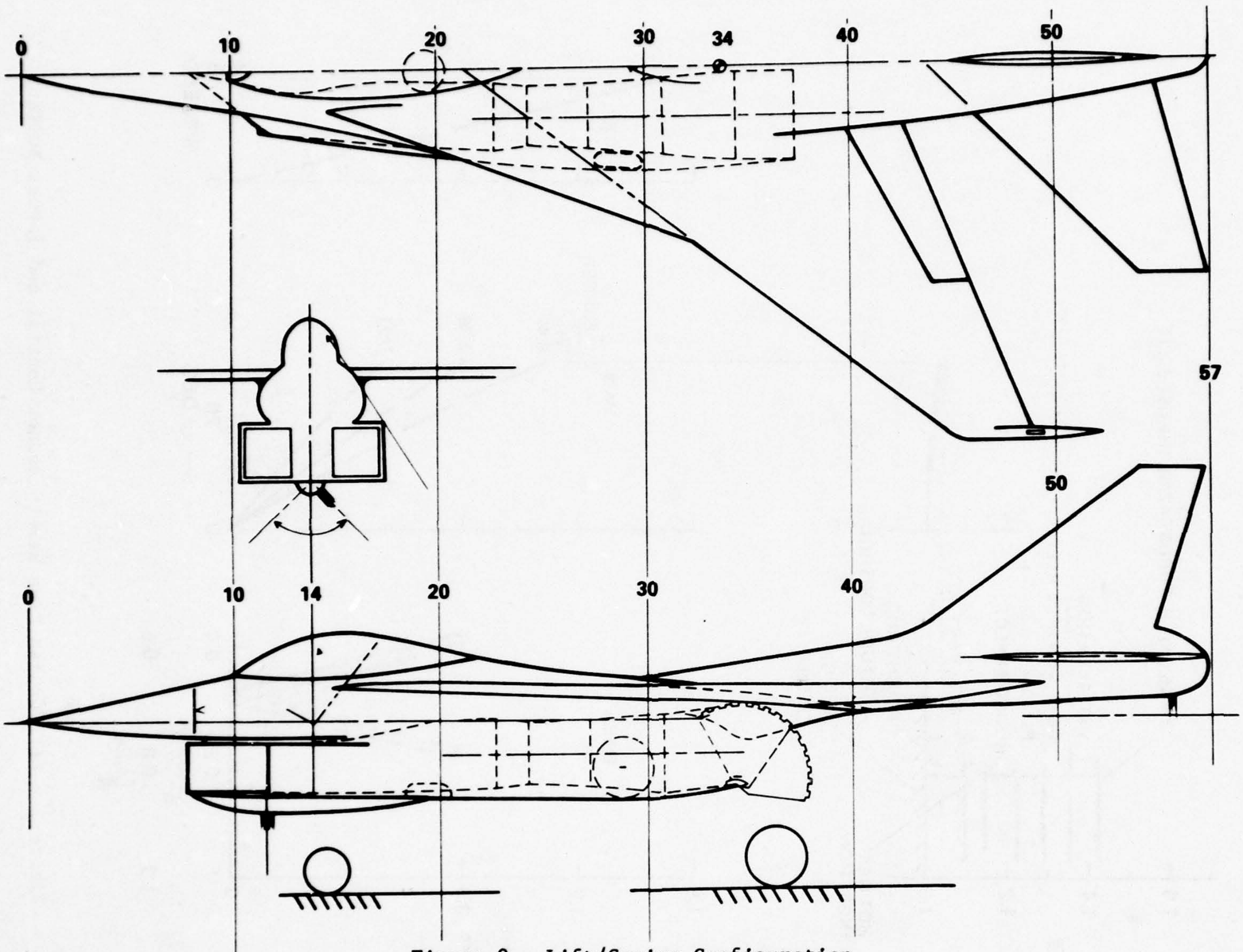


Figure 8 - Lift/Cruise Configuration

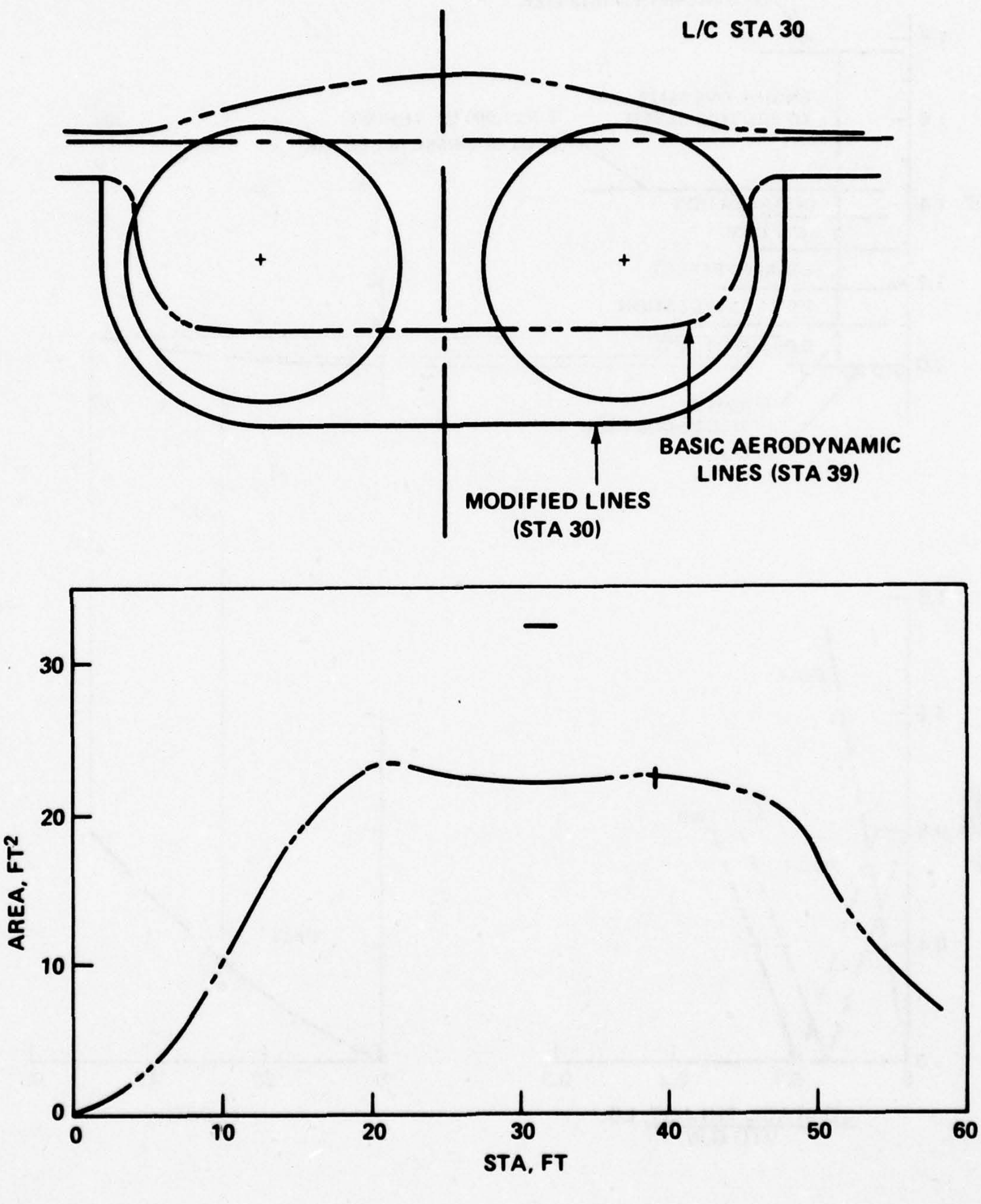


Figure 9 - Lift/Cruise Effect on Aerodynamic Lines

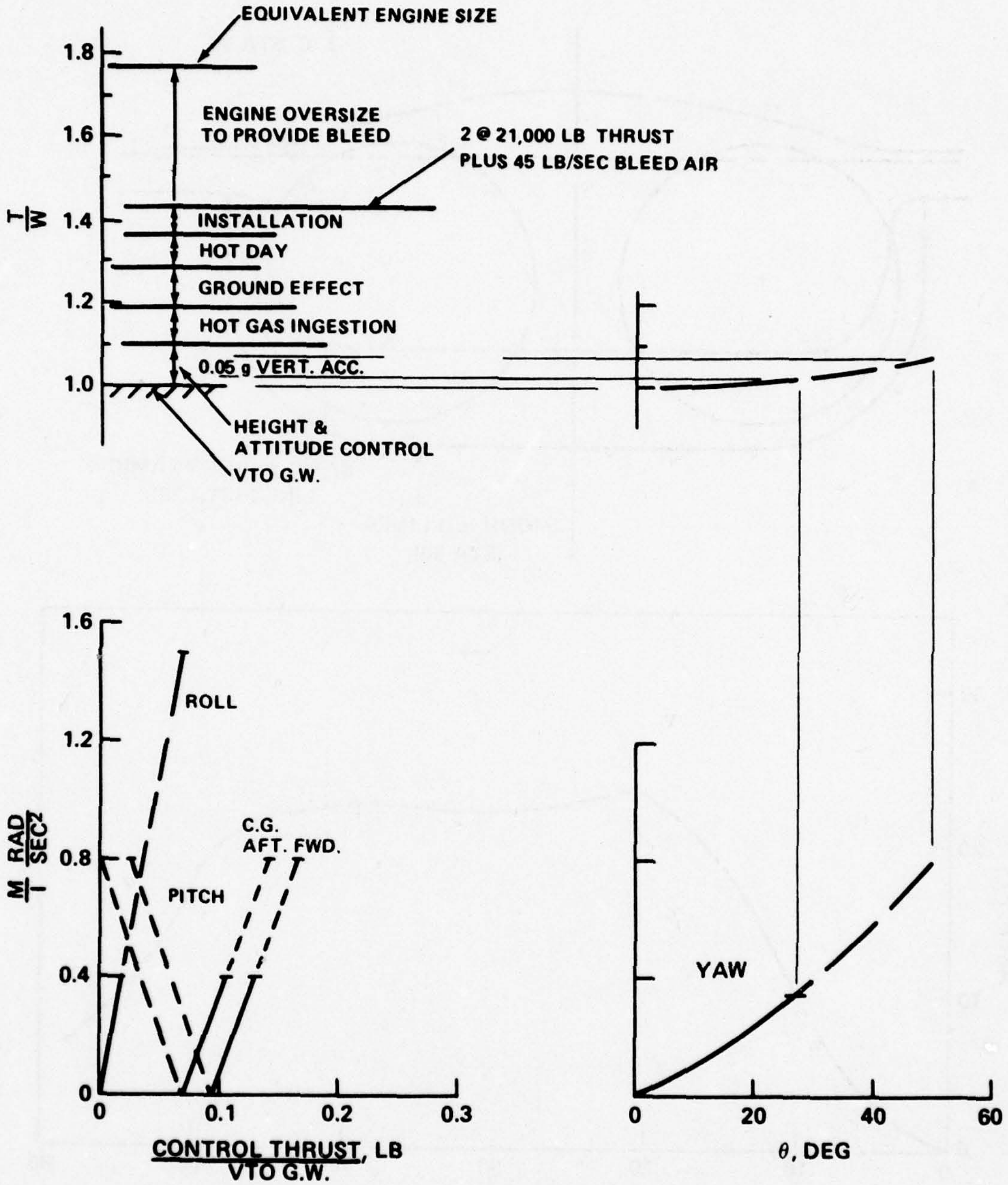


Figure 10 - Lift/Cruise Bleed Air Control

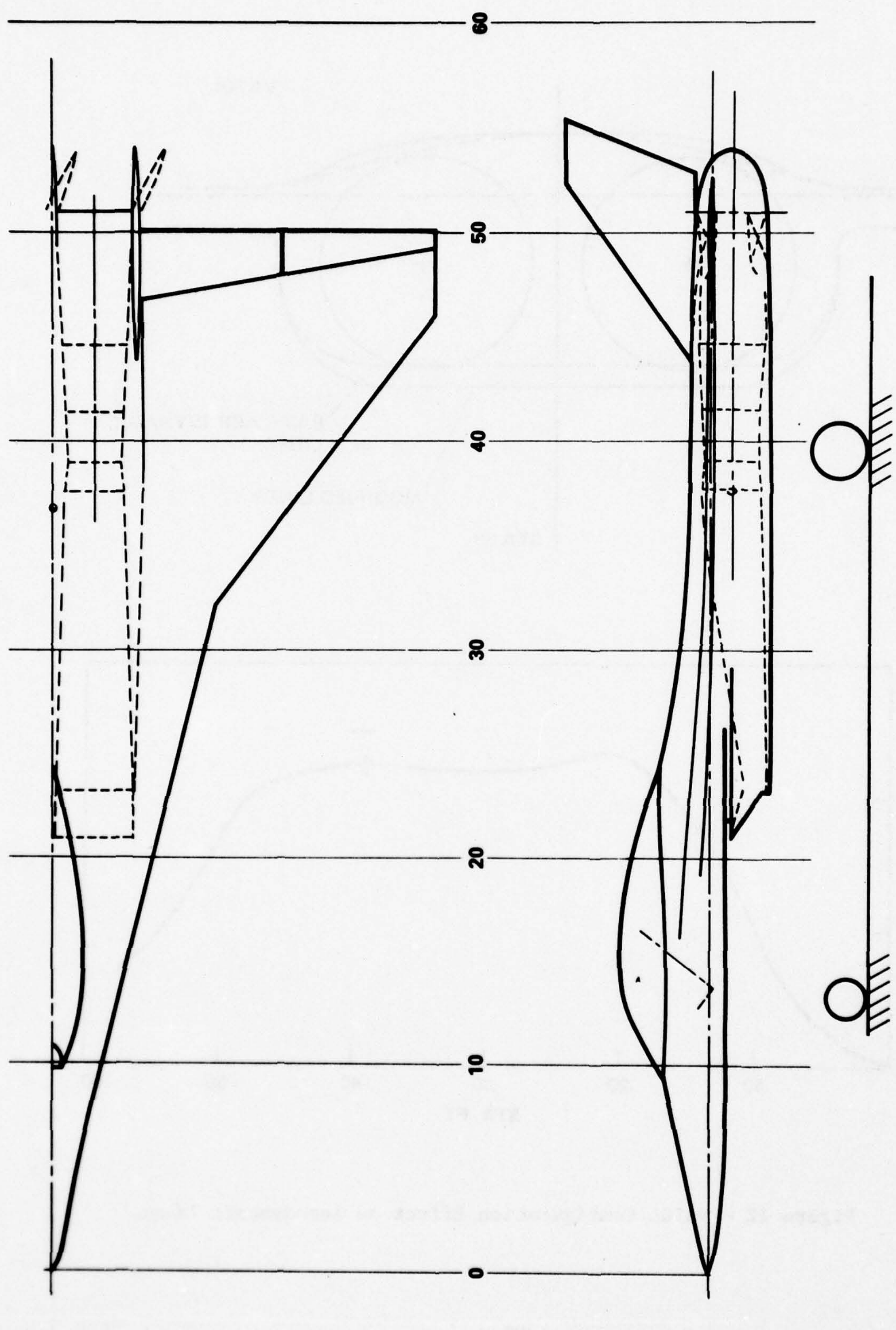


Figure 11 - VATOL Configuration

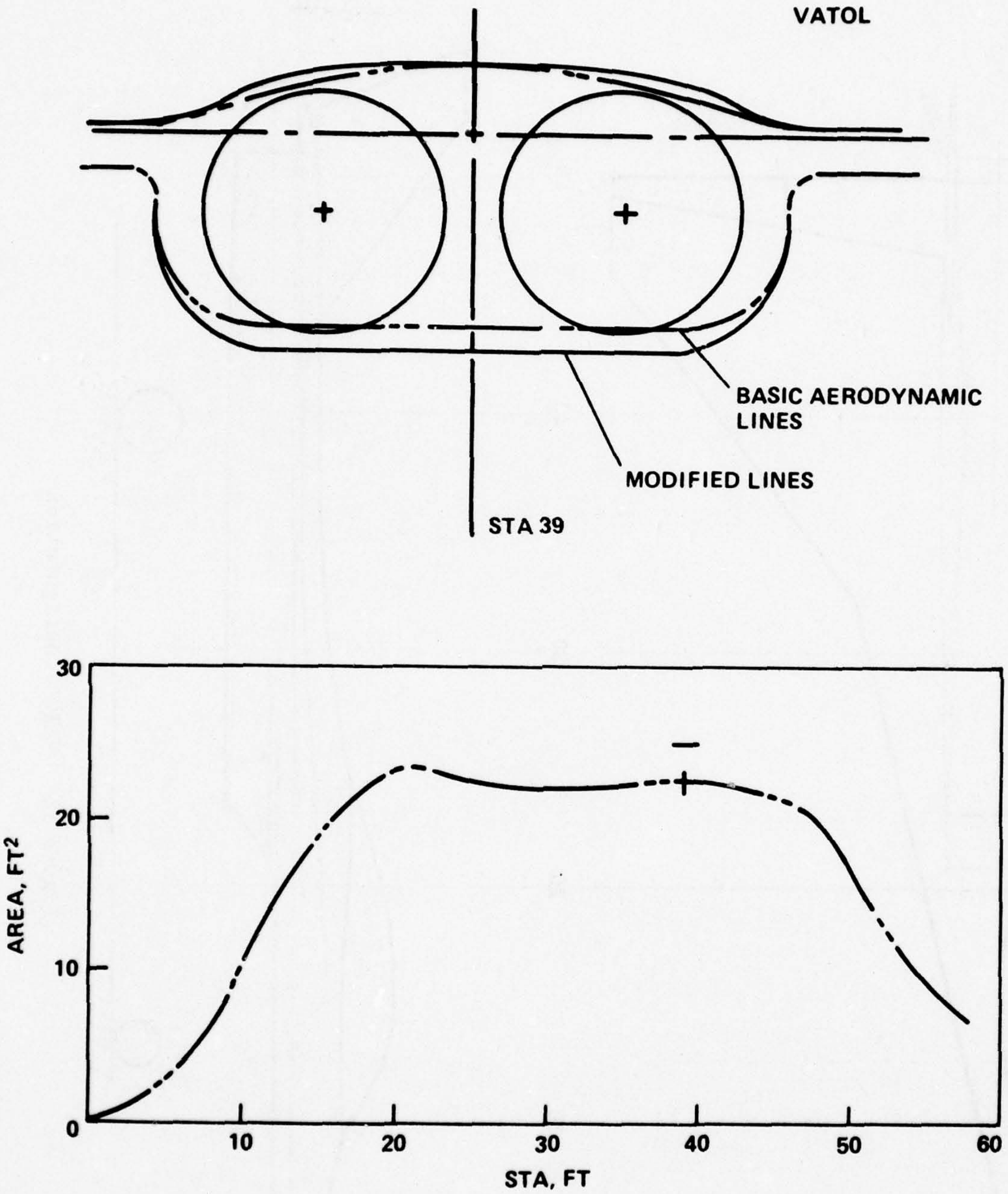


Figure 12 - VATOL Configuration Effect on Aerodynamic Lines

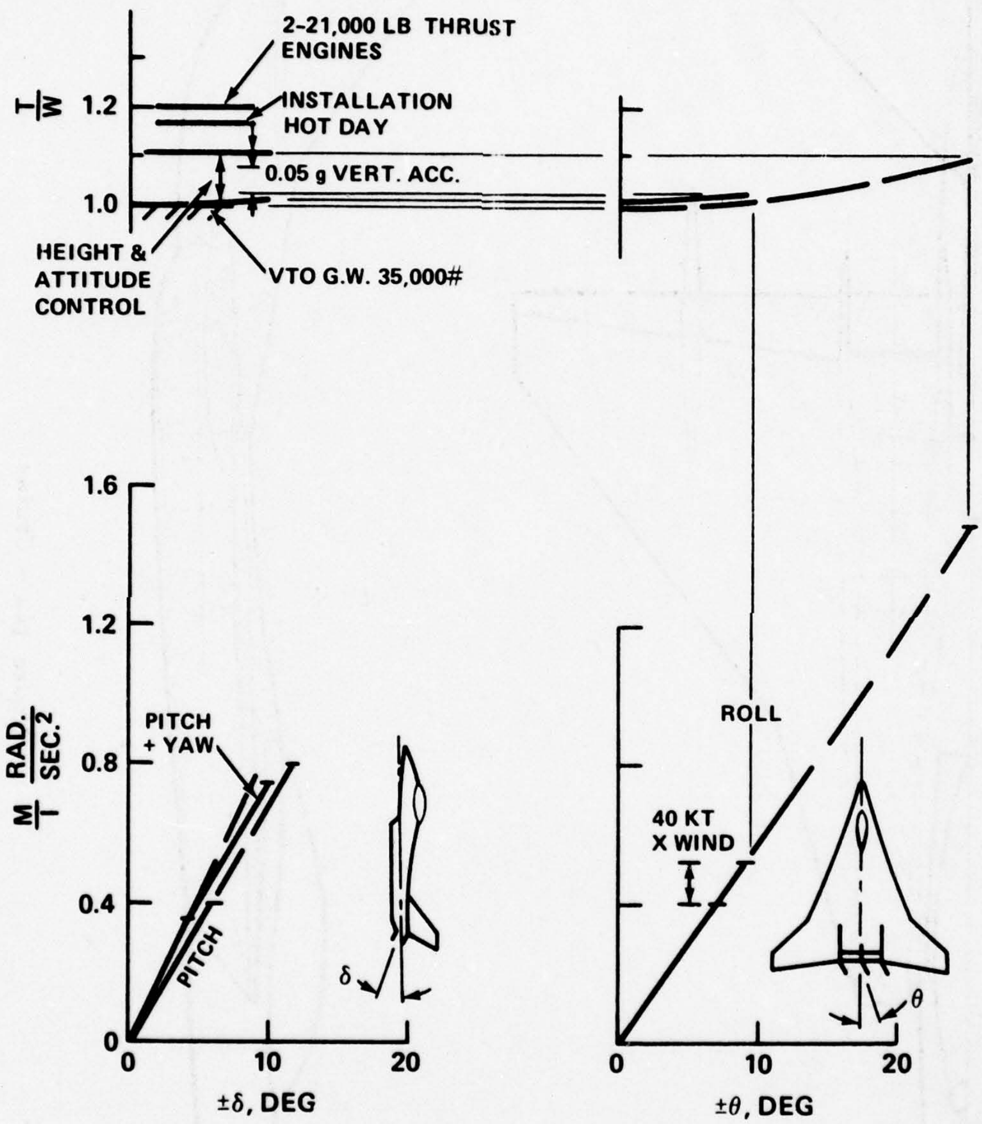
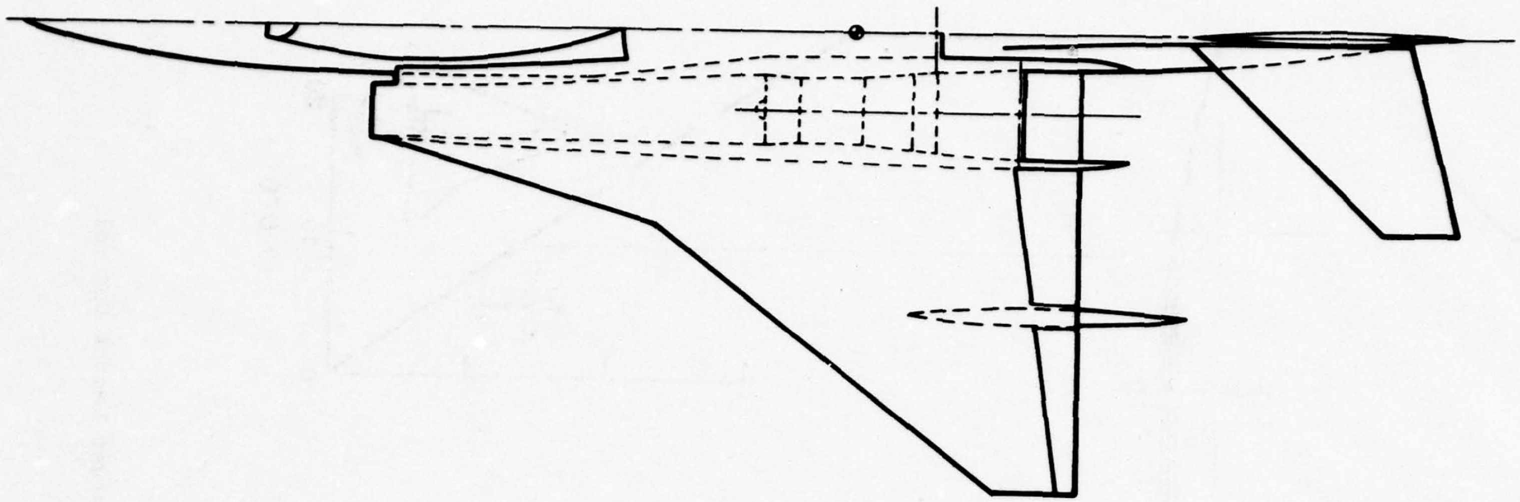


Figure 13 - VATOL Thrust Vector Control

Figure 14 - Tilt Wing Configuration



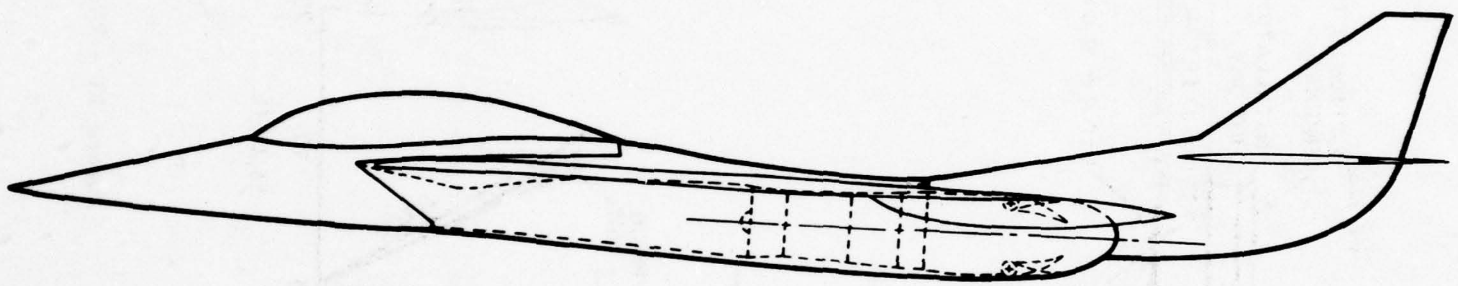


Figure 14a - Cruise

Figure 14 (Continued)

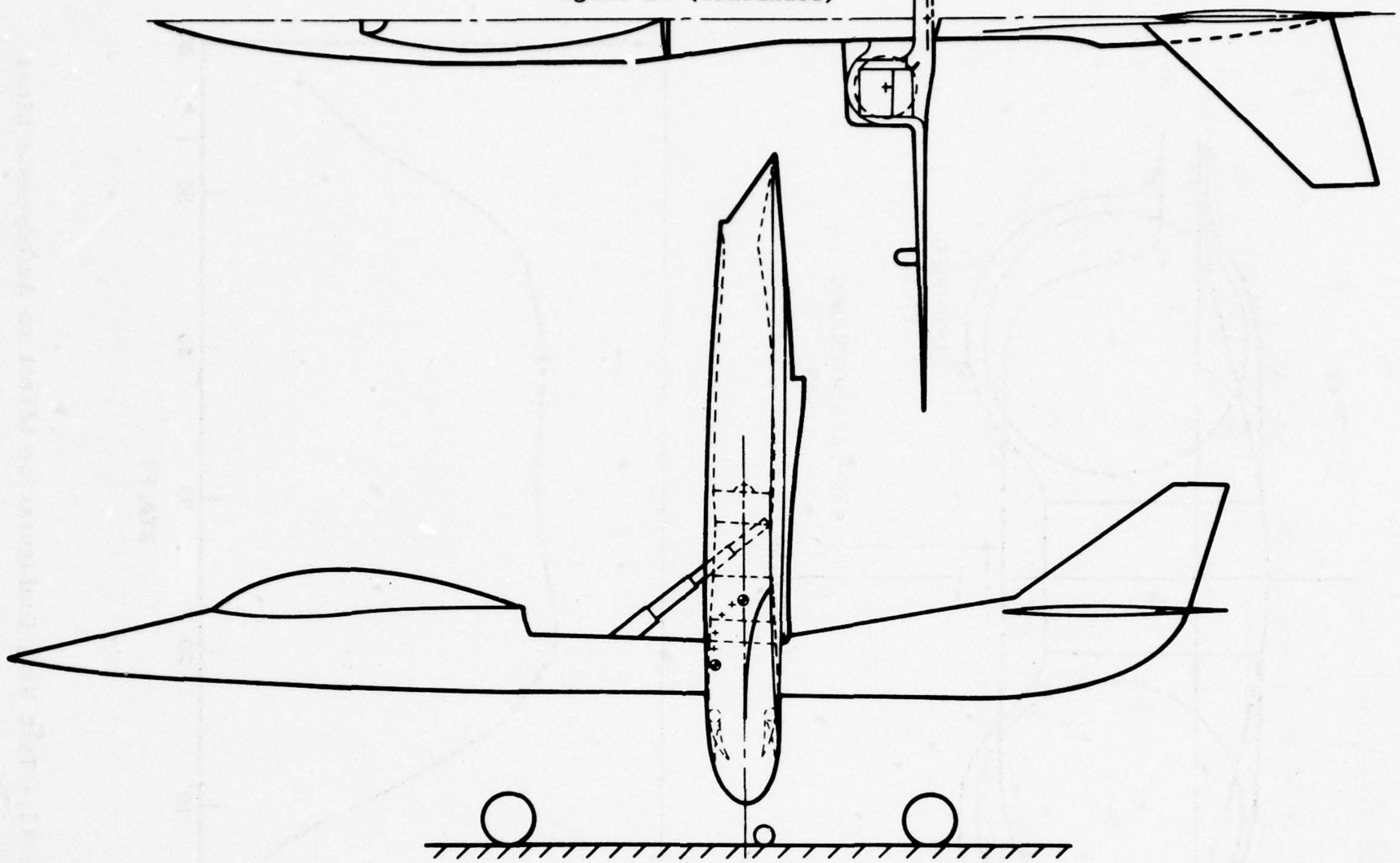


Figure 14b - Takeoff and Landing

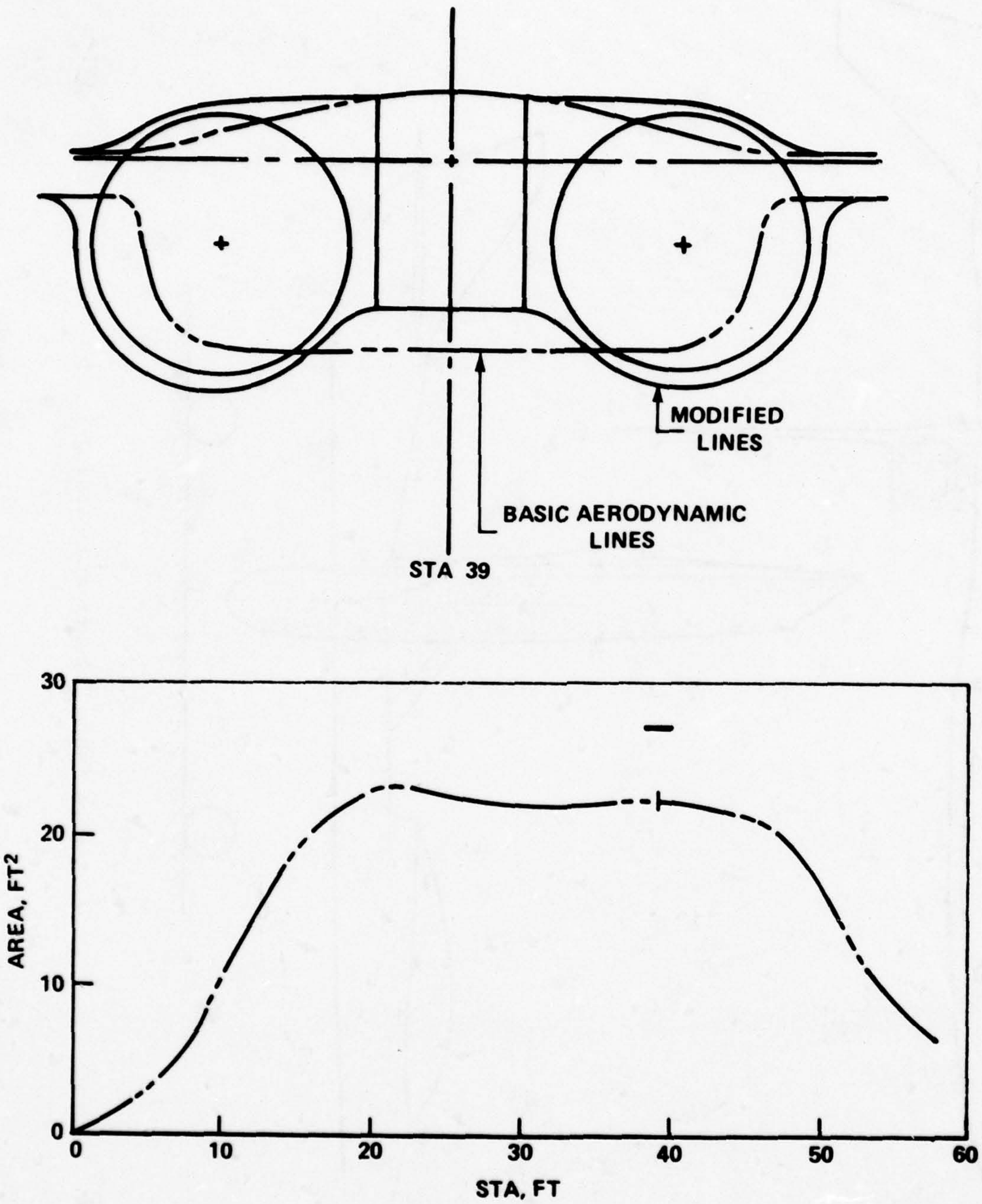


Figure 15 - Tilt Wing Configuration Effect on Aerodynamic Lines

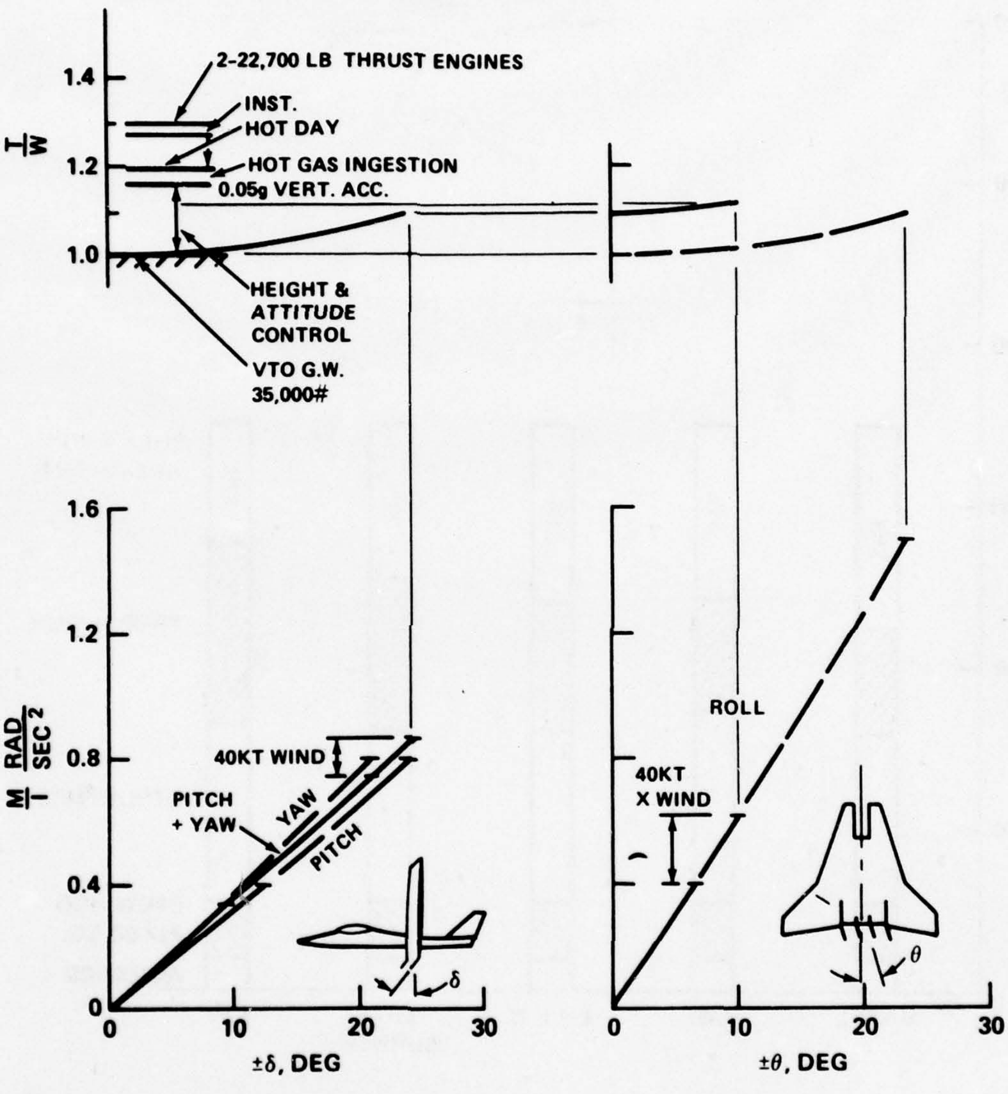


Figure 16 - Tilt Wing Thrust Vector Control

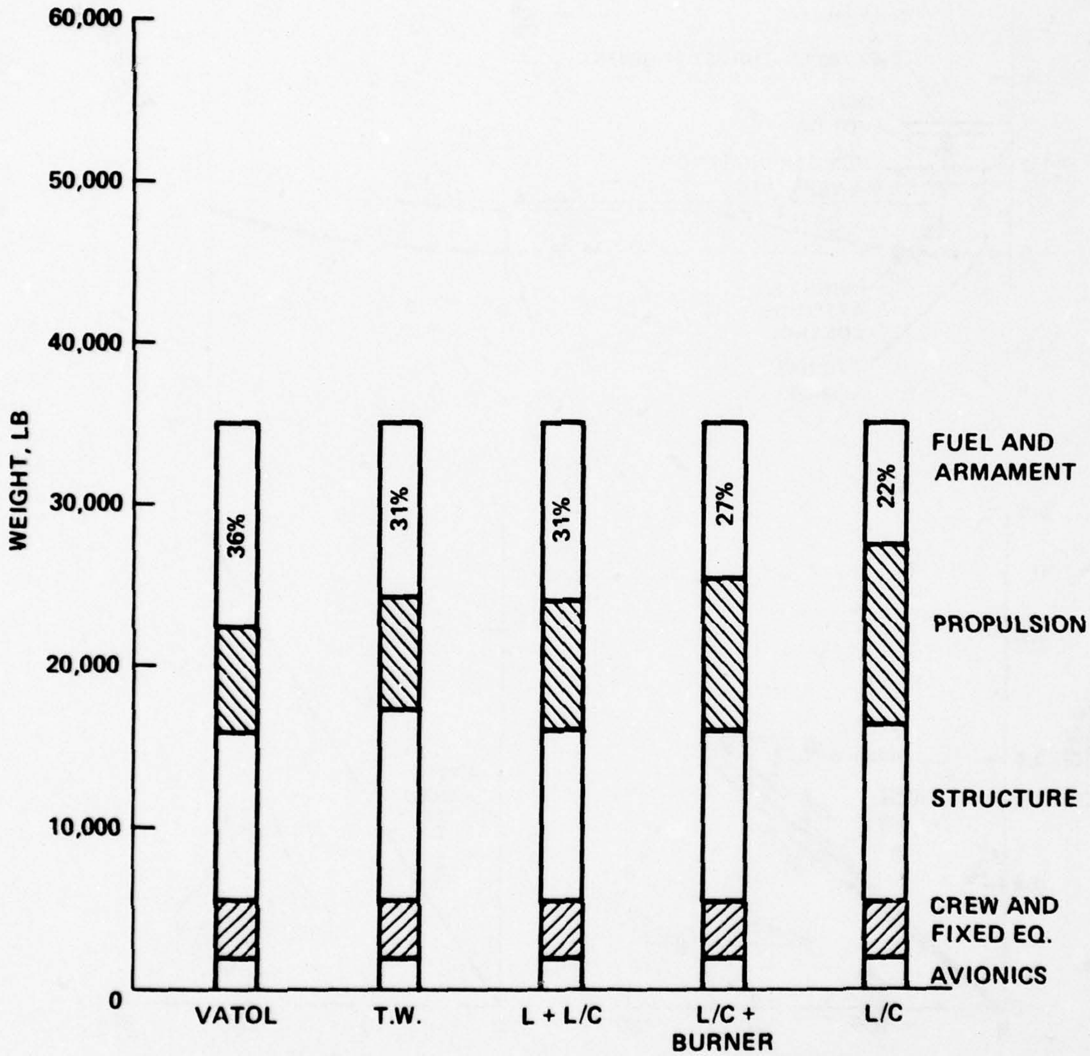


Figure 17 - Weight Breakdown of VTOL Configurations

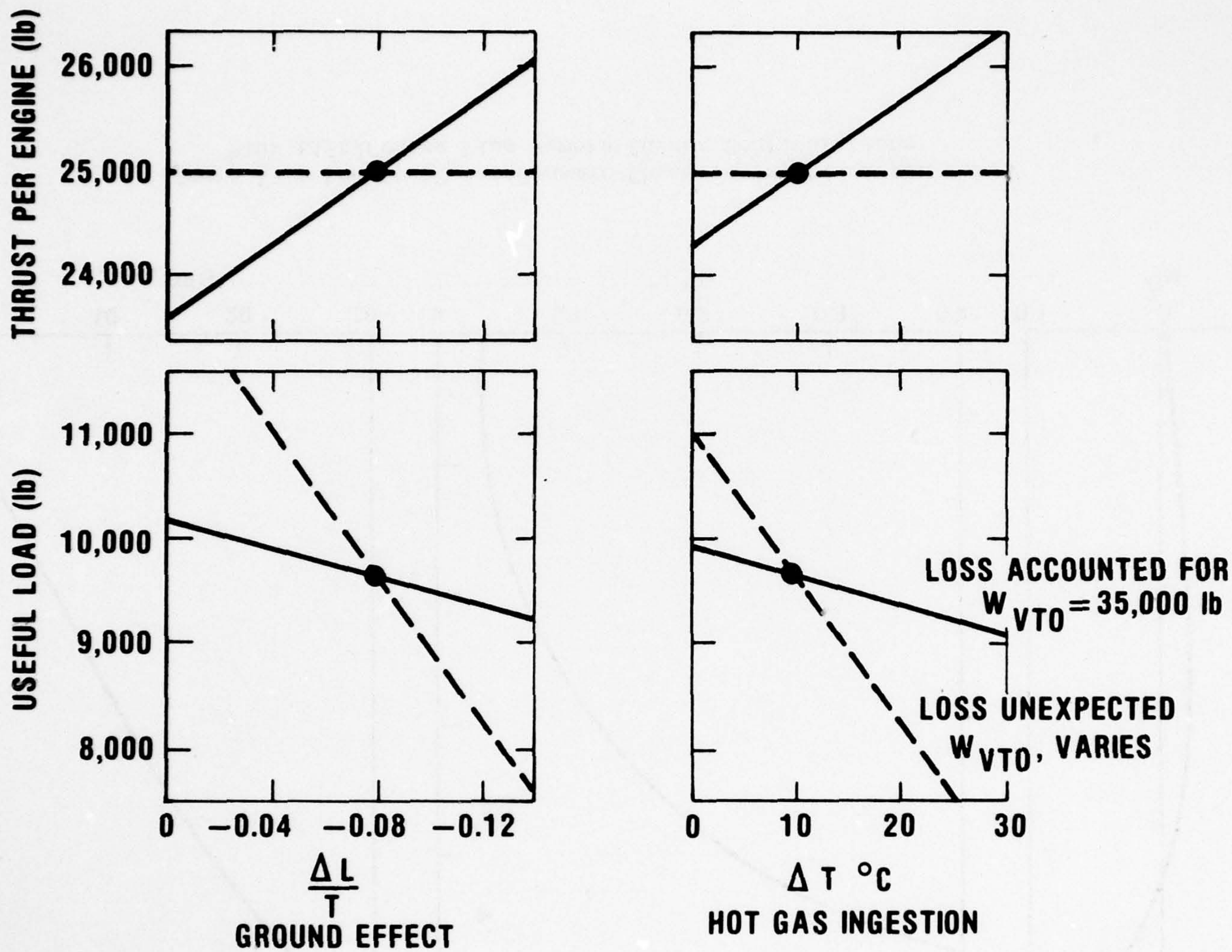


Figure 18 - Sensitivity to Installation Losses VTO Performance

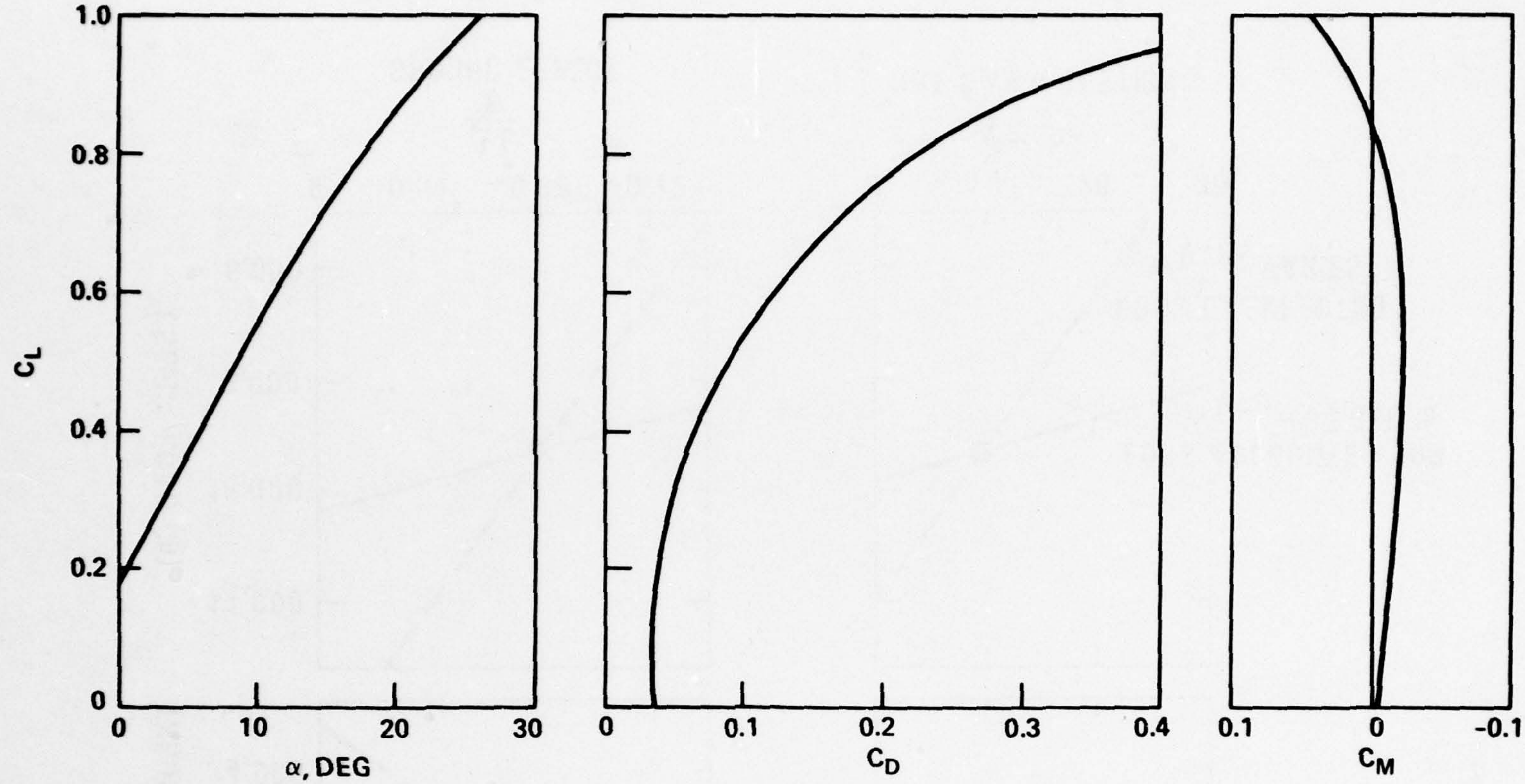


Figure 19 - Low-Speed Aerodynamic Characteristics of the Lift Plus Lift/Cruise Plus Remote Burner Configurations

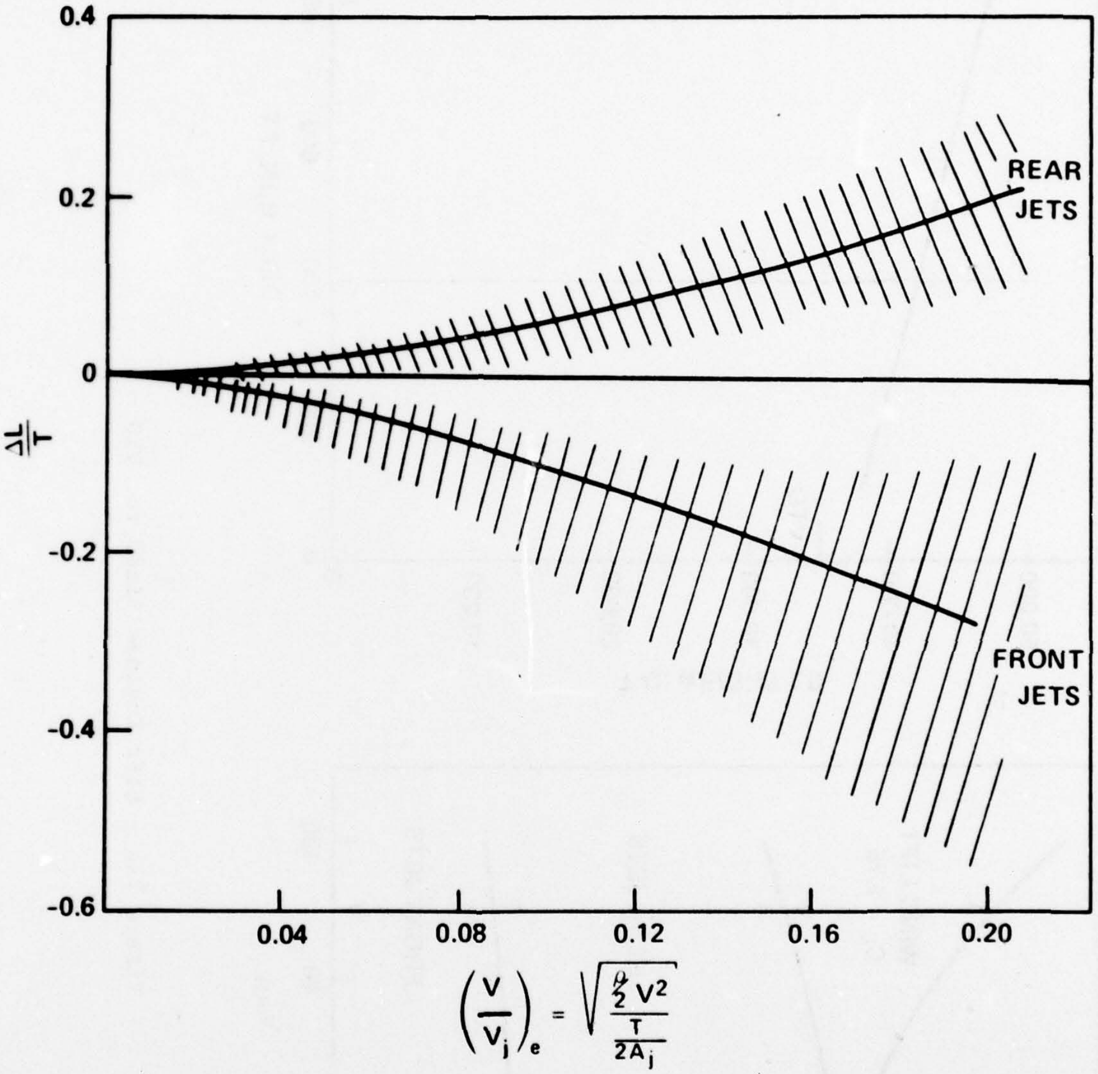


Figure 20 - Jet Induced Effects

Figure 21 - Overload Performance for Lift Engines

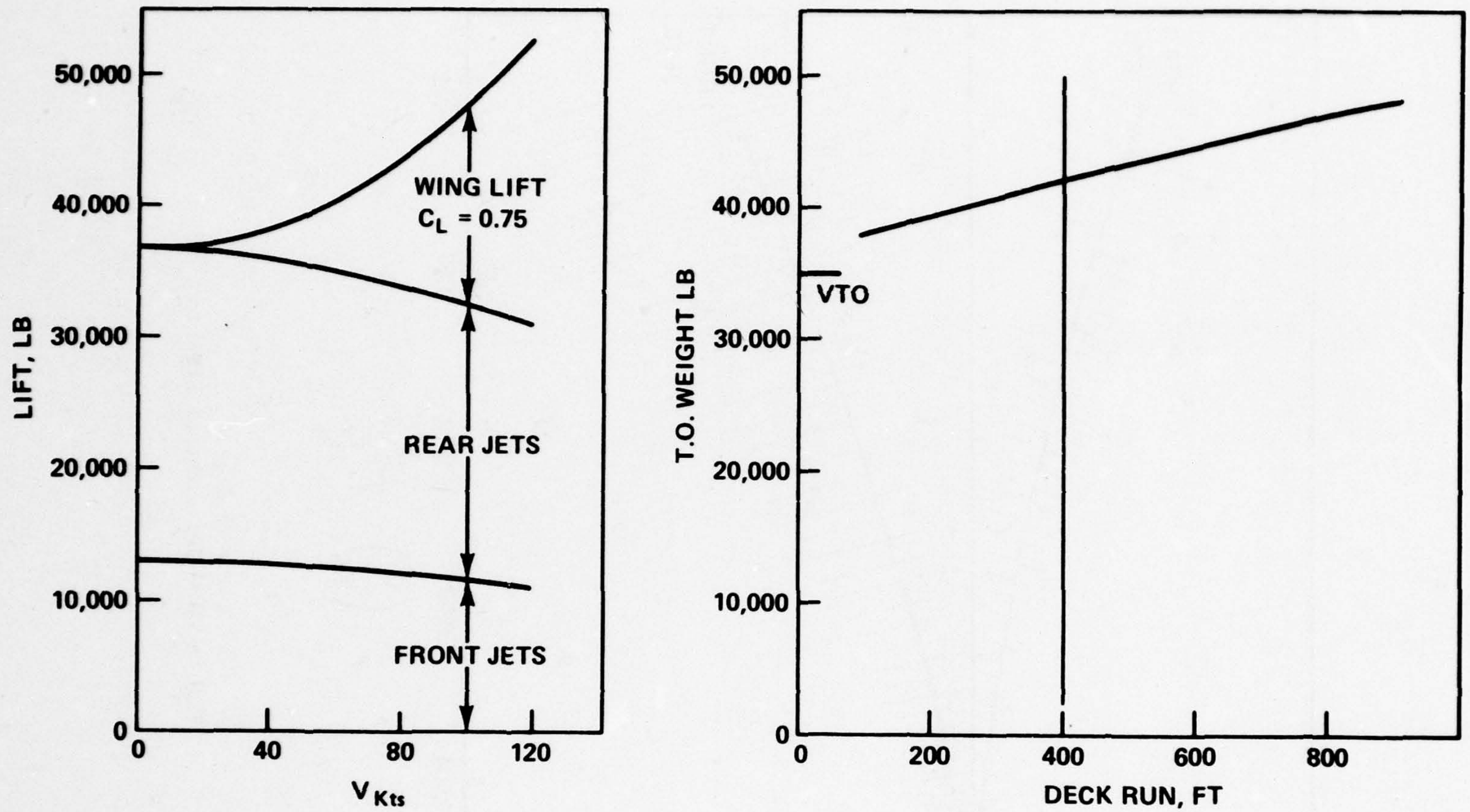


Figure 21a - Lift Engines Sized for VTO

Figure 21 (Continued)

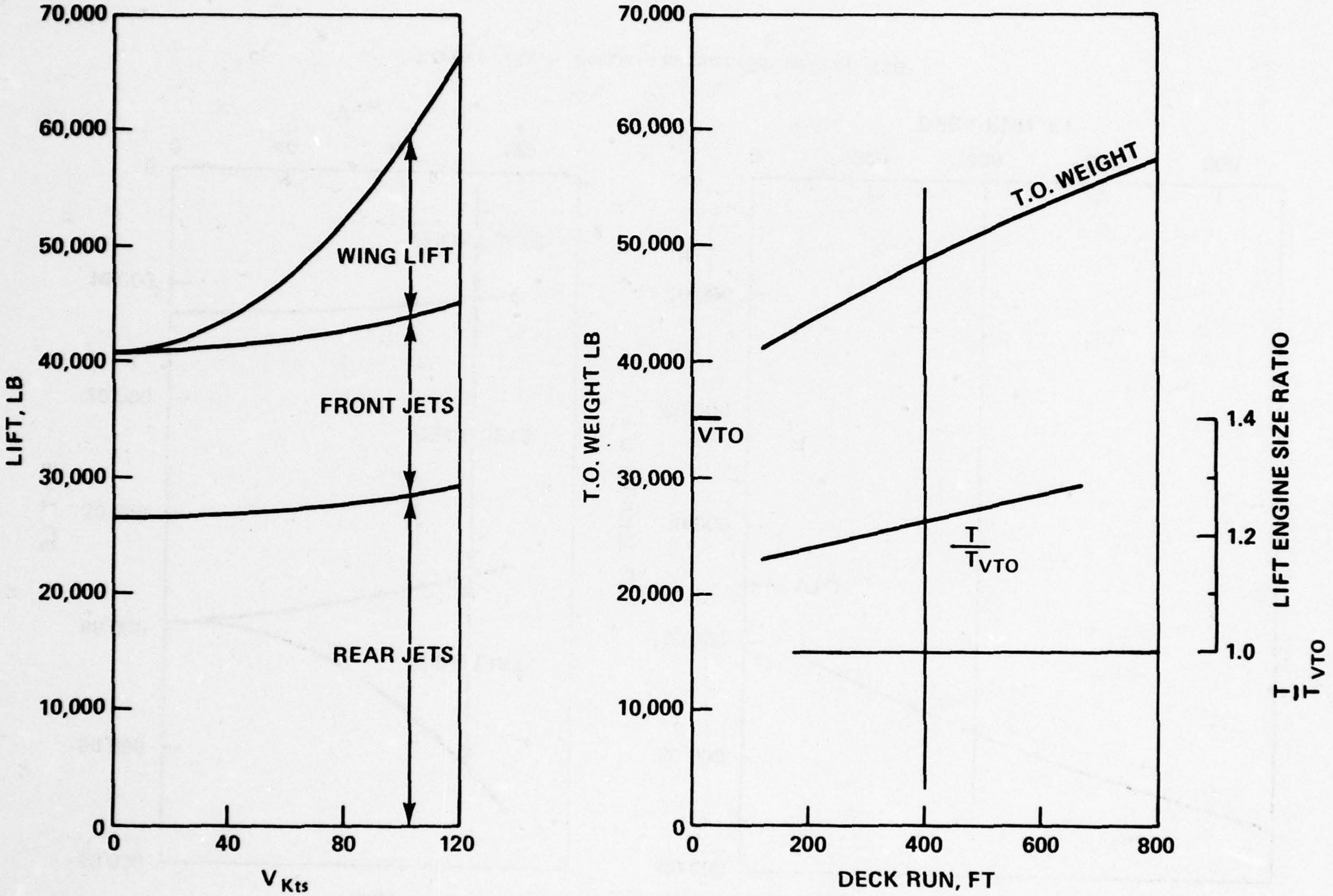


Figure 21b - Lift Engines Sized for STO

Figure 22 - Overload Performance for Remote Burner

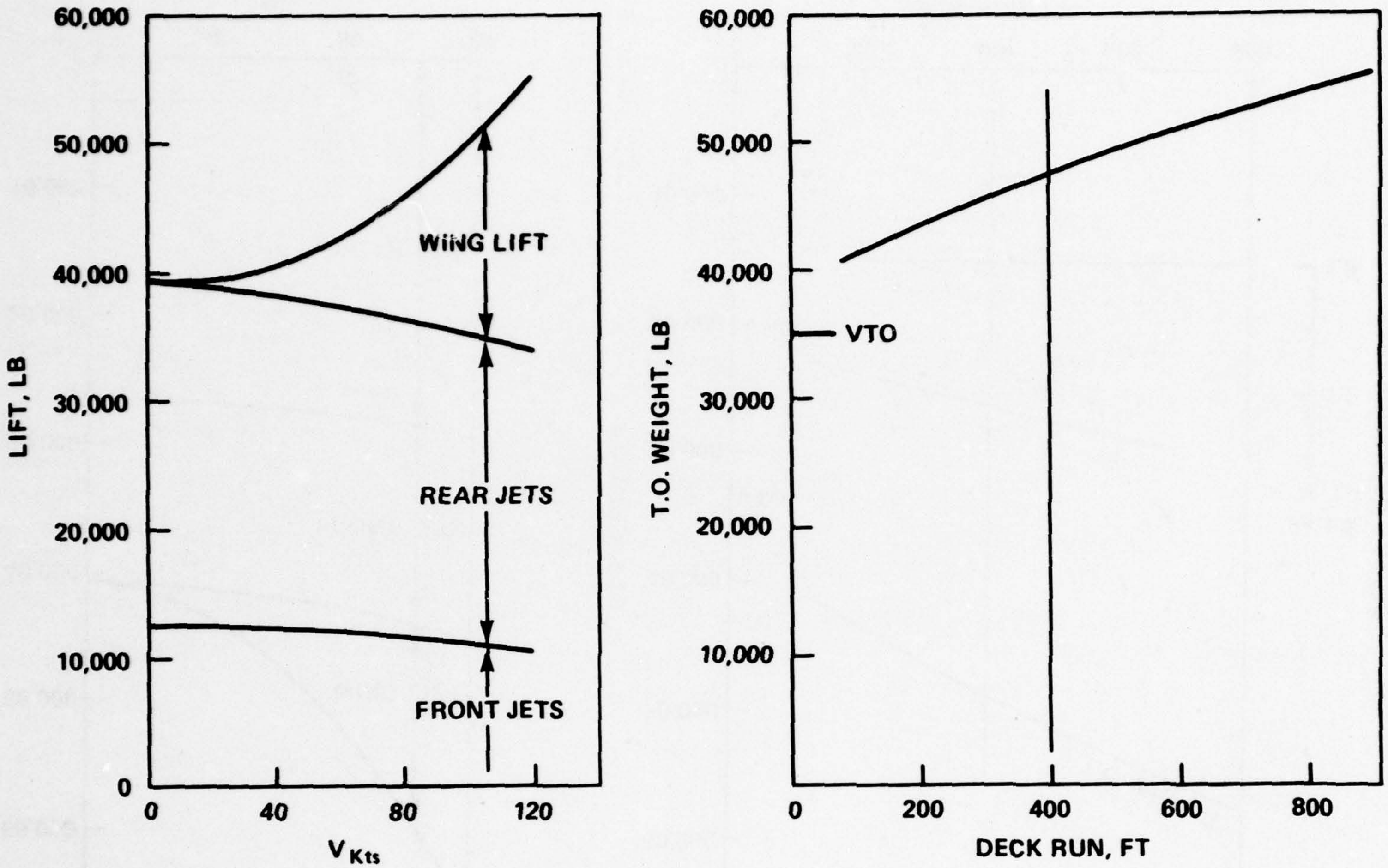


Figure 22a - Remote Burner Sized for VTO

Figure 22 (Continued)

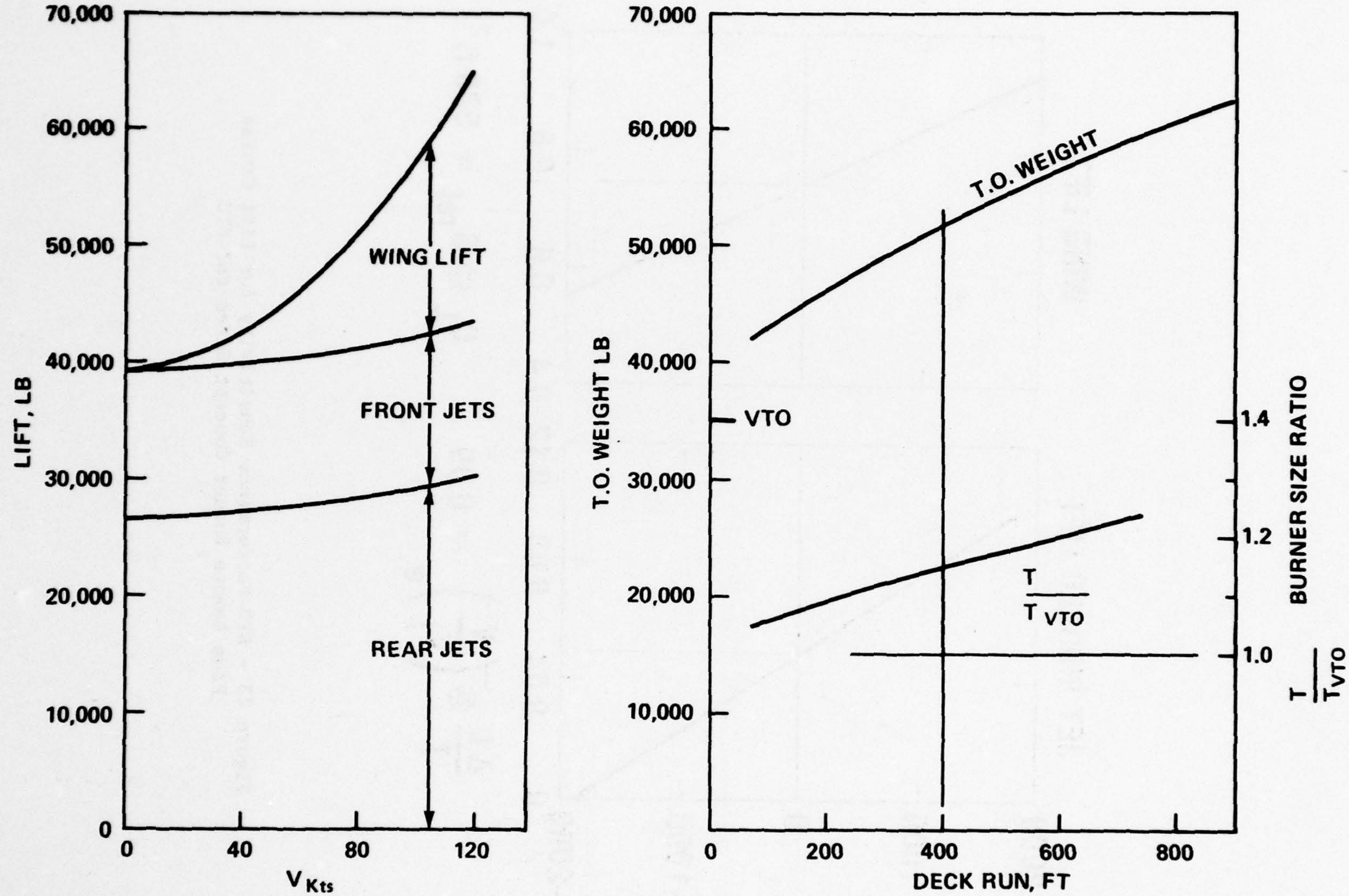


Figure 22b - Remote Burner Sized for STO

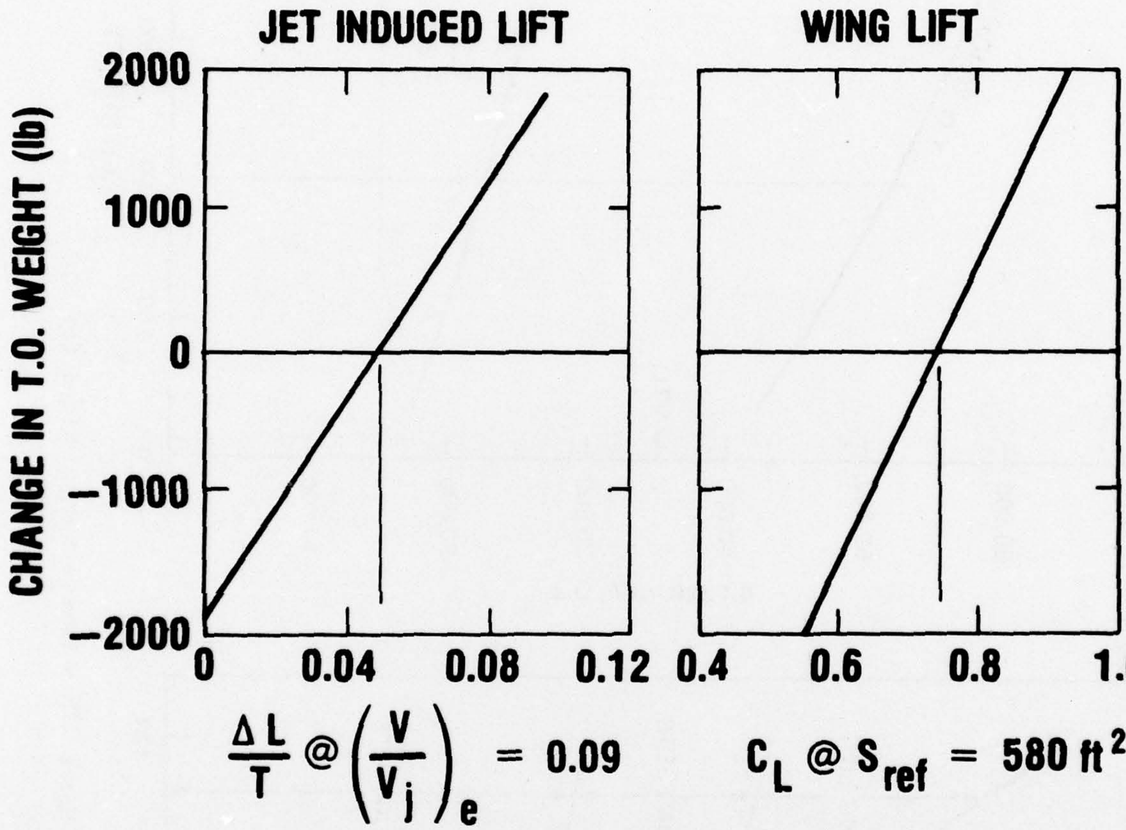


Figure 23 - STO Performance Sensitivity for Lift Cruise Plus Remote Burner Concept Sized for STO

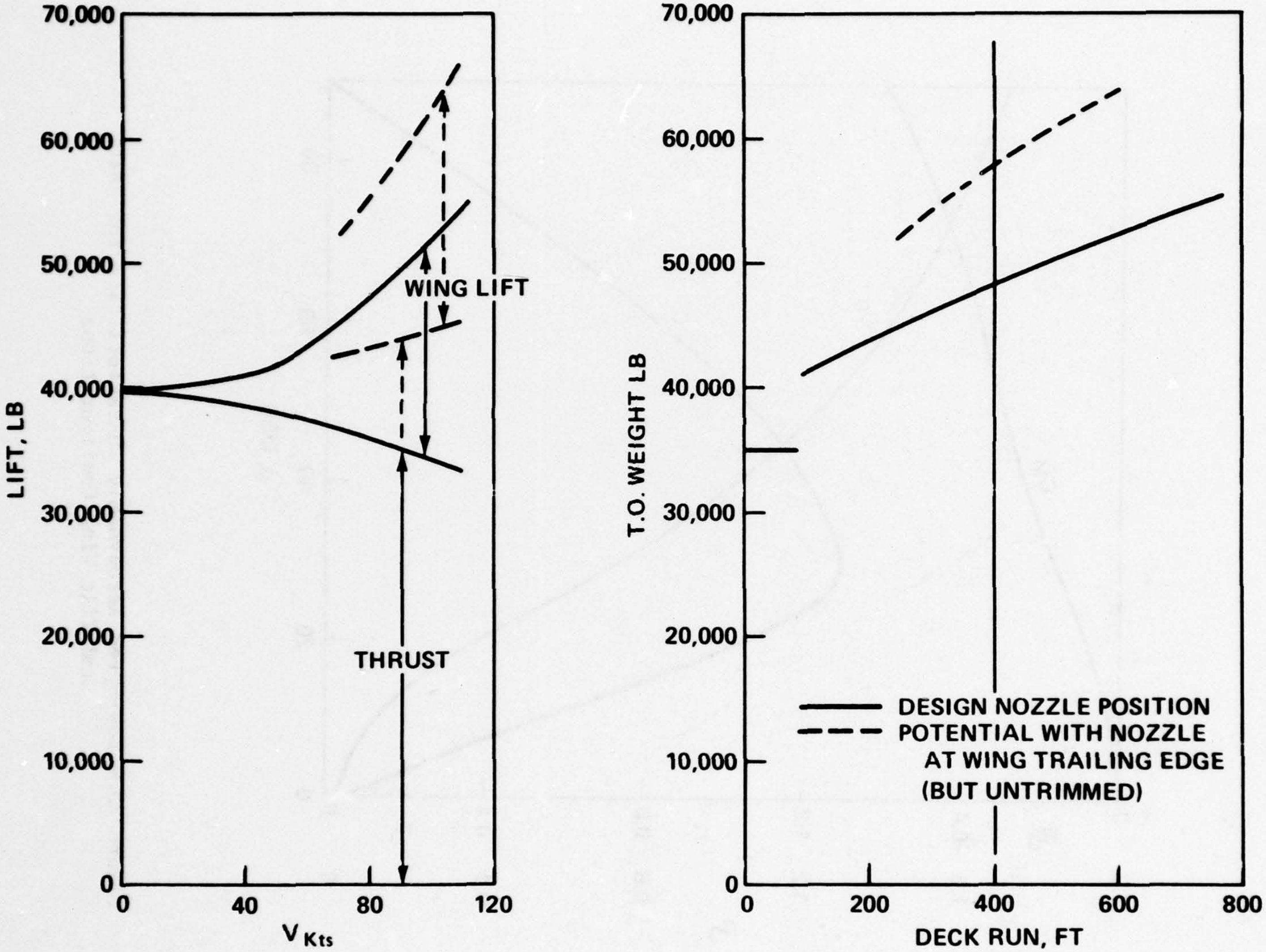


Figure 24 - Overload Takeoff Performance for Lift/Cruise Configuration

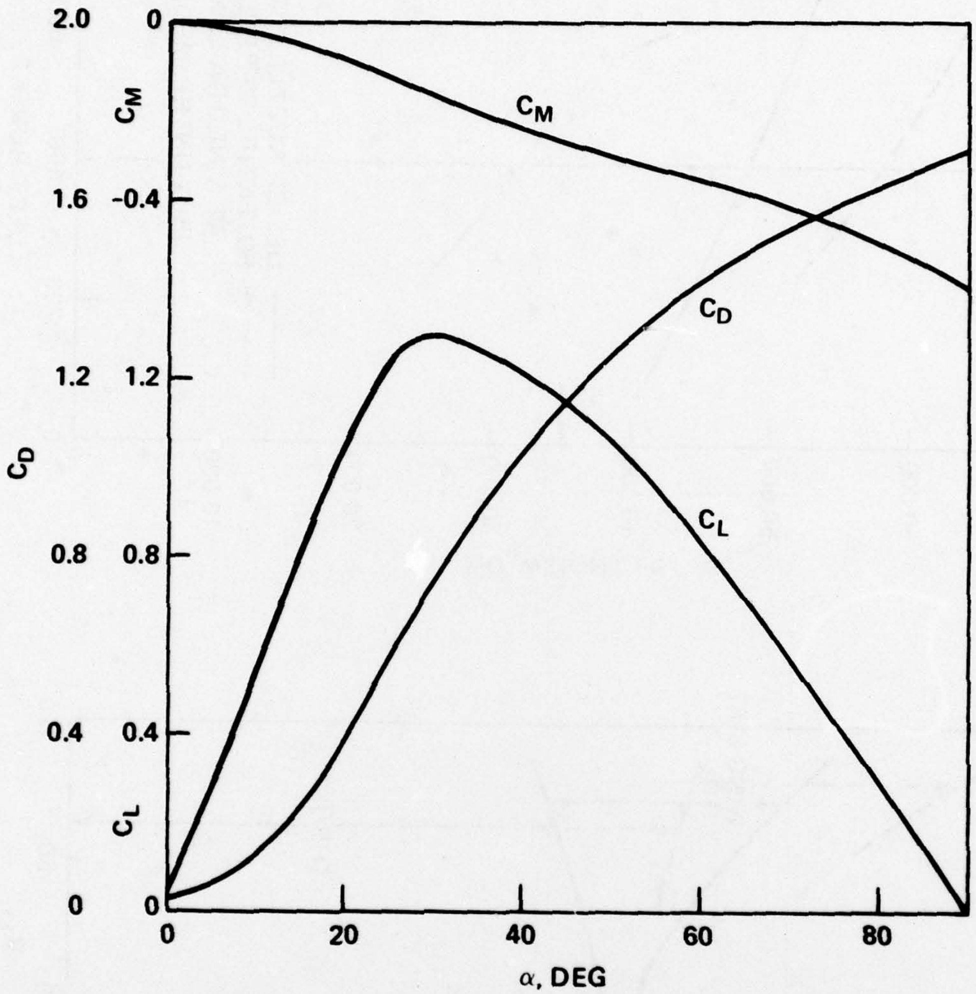


Figure 25 - Low-Speed Aerodynamic Characteristics for VATOL and Tilt Wing Configurations

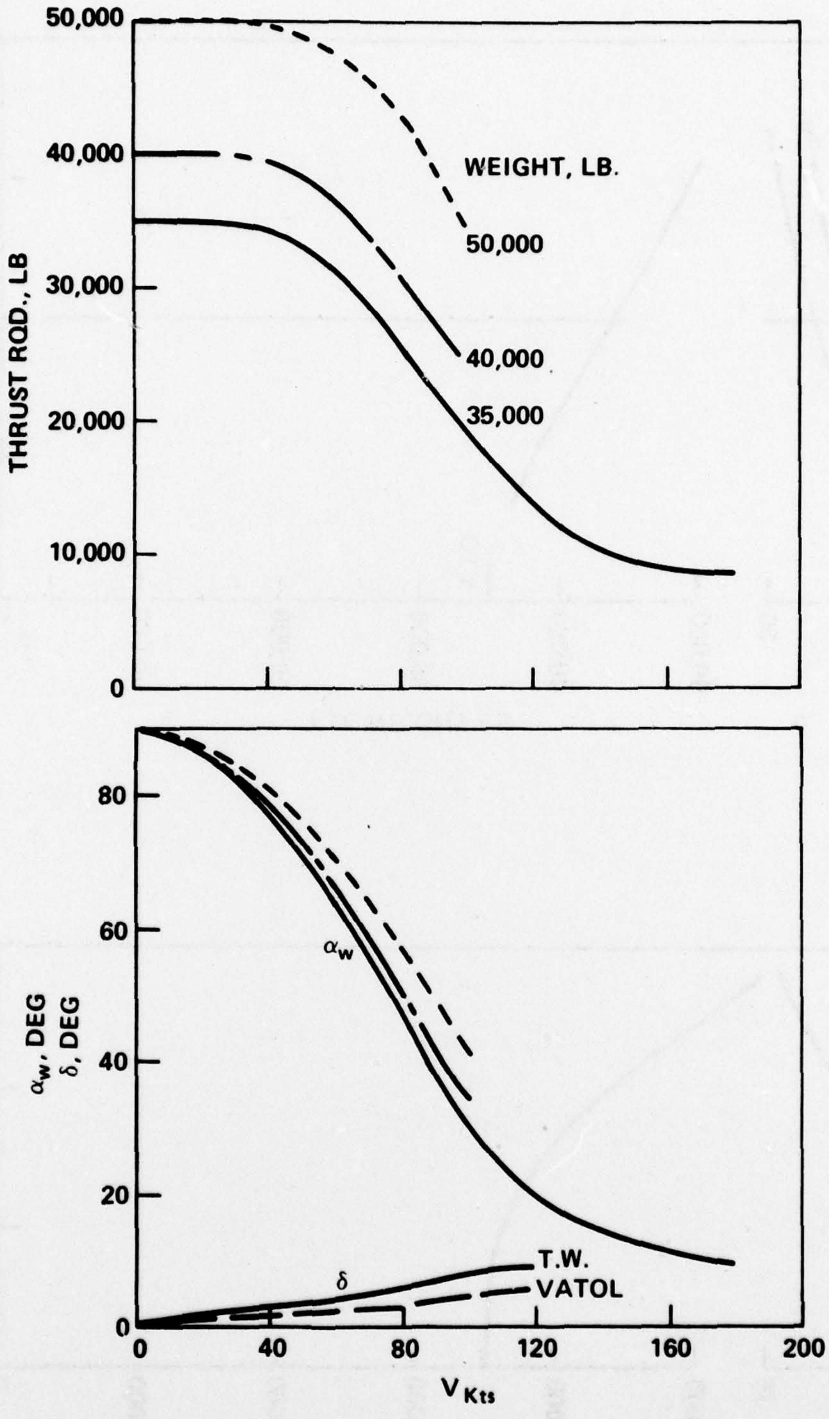


Figure 26 - Transition Performance for VATOL and Tilt Wing Configurations

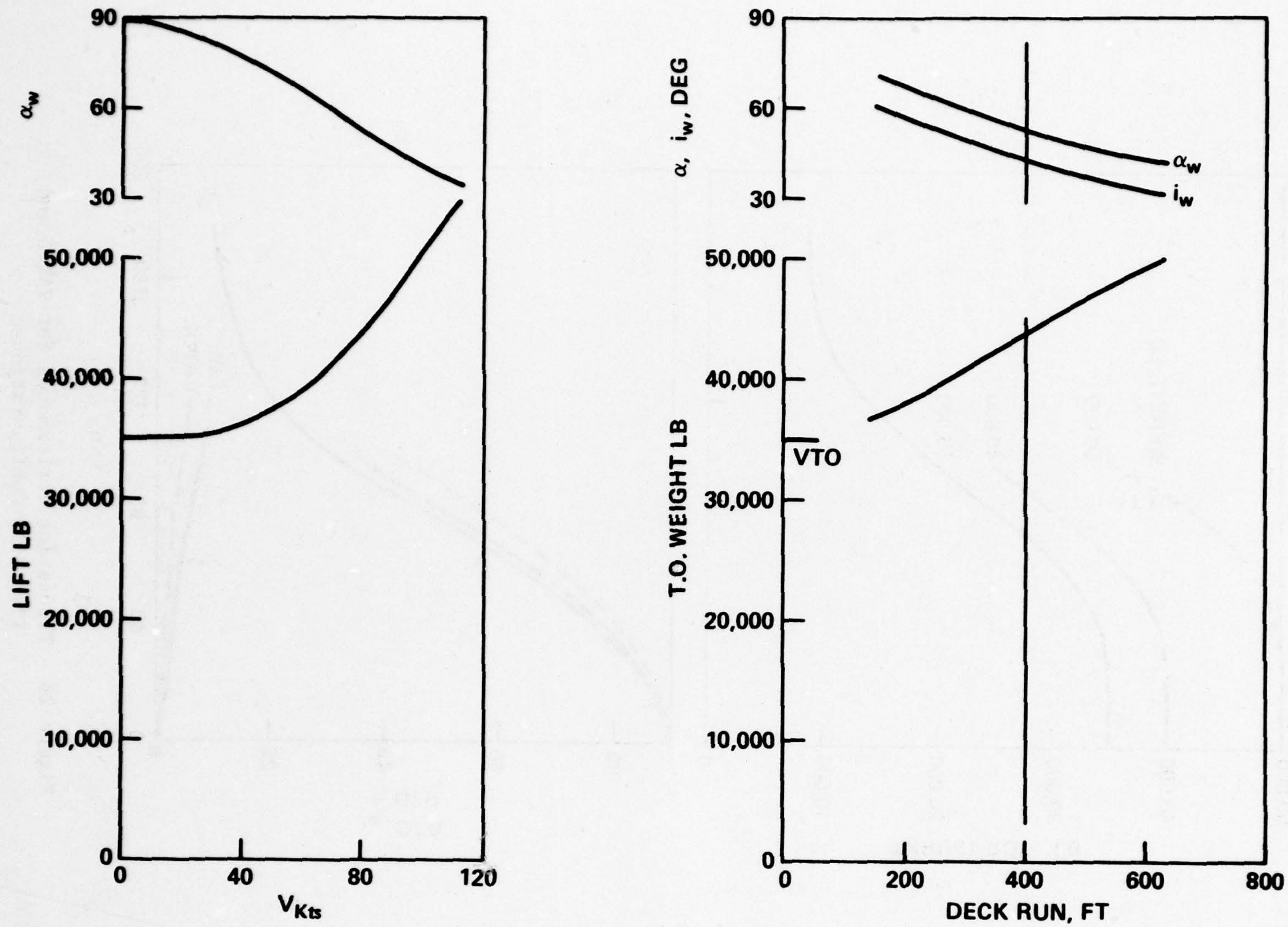


Figure 27 - Overload Performance for Tilt Wing Configuration

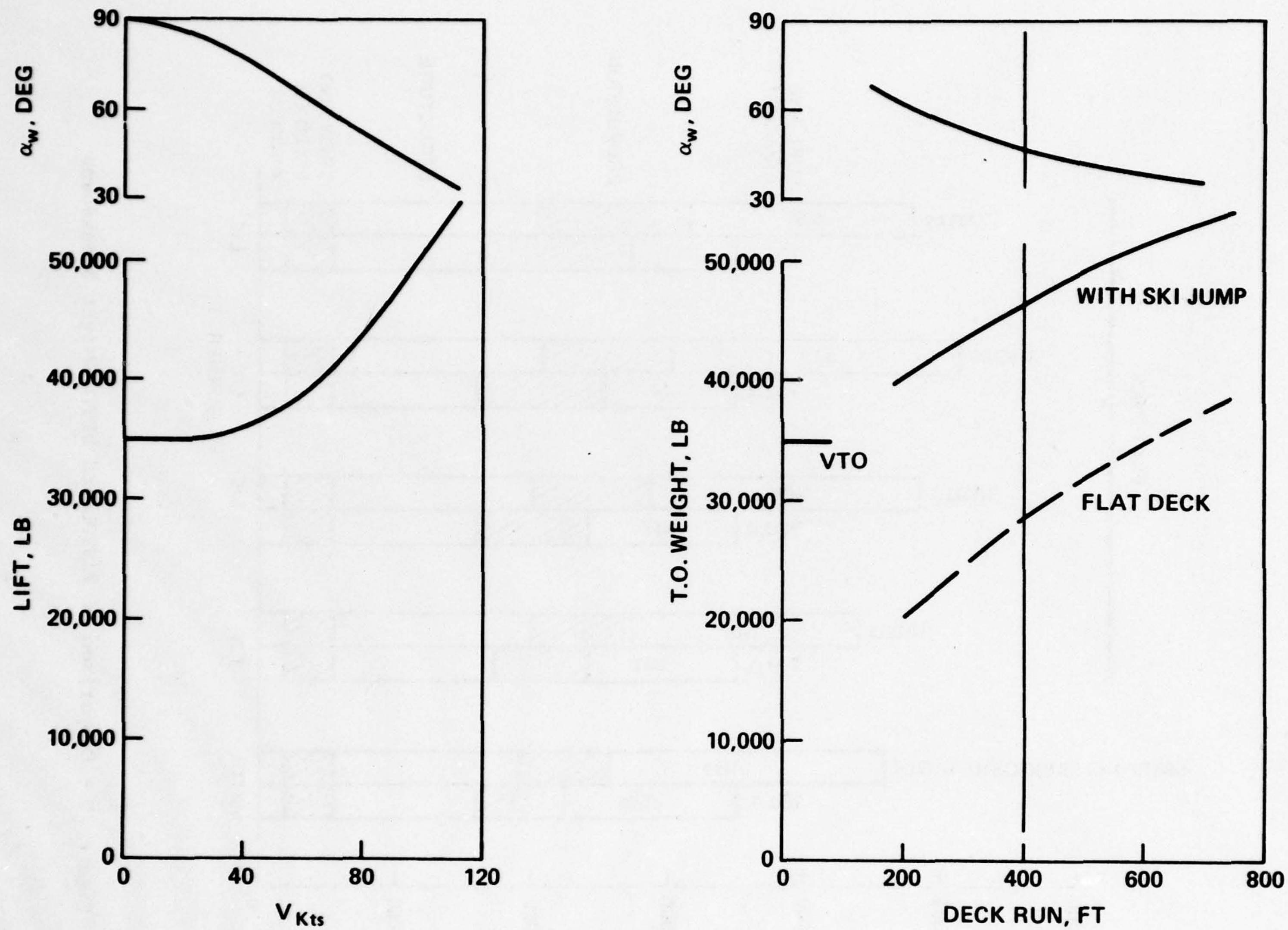


Figure 28 - Overload Performance for VATOL Configuration

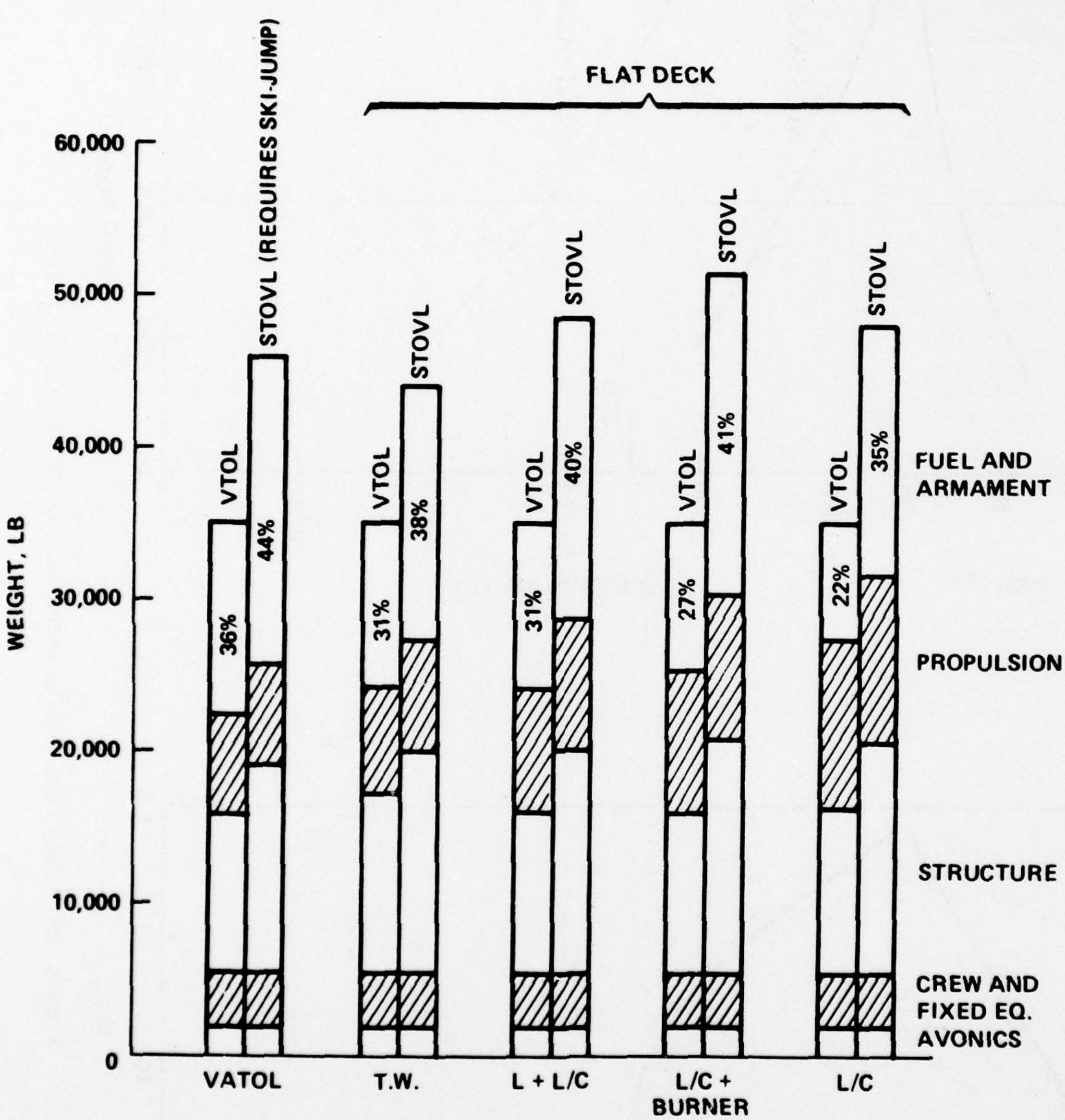


Figure 29 - Comparison of V/STOL and STOVL Weight Breakdowns

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